STUDIES IN CEREAL DISEASES

XI

The Prevention of Cereal Rusts by the Use of Fungicidal Dusts

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TABLE OF CONTENTS

PAGE

I. Introduction ... 5

II. Historical review
- Plant disease control by dusting ... 6
- Sulphur as a fungicide ... 7
- The prevention of cereal rusts by the use of chemicals ... 8

III. Objects of investigation ... 9

IV. Experimental work

A. Laboratory studies ... 10
- *Materials and methods* ... 10
- *Experimental results*
  - Relative toxicity of sulphur and copper dusts ... 11
  - Toxicity of various sulphur dusts ... 16
  - Toxicity of oxidized sulphur dusts ... 16
  - Relative toxicity of inert and sulphur dusts ... 17

B. Greenhouse studies ... 18
- *Materials and methods* ... 18
- *Experimental results*
  - Relative fungicidal value of sulphur and copper dusts ... 19
  - Fungicidal effectiveness of various sulphur dusts ... 22
  - Fungicidal effectiveness of oxidized sulphur dusts ... 23
  - Factors influencing the fungicidal effectiveness of sulphur dusts ... 25
  - Effect of sulphur on the type of rust infection ... 30

C. Field experiments on the prevention of cereal rusts by sulphur dusting
- *Observations on severity of rust epidemics in Manitoba* ... 31
- *Preliminary field dusting tests* ... 32
- *Small plot experiments* ... 35
  - Materials and methods ... 35
  - Experimental results

The prevention of leaf rust and stem rust of wheat
- *Effect of rate of dust application* ... 38
- *Interval between dust applications* ... 45
- *Effectiveness of various dust fungicides* ... 47
- *Effect of initial time of dusting* ... 52
- *Method of dust application* ... 55
- *Effect of meteorological conditions on dusting* ... 56
- *Effect of sulphur as a fertilizer* ... 57

The prevention of crown rust and stem rust of oats ... 58
- *Experiments in 1929* ... 58
- *Experiments in 1930* ... 59
- *Experiments in 1931* ... 60

Sulphur dusting for the prevention of minor leaf and stem diseases of wheat ... 63
- *Wheat scab control* ... 64
- *Black chaff control* ... 64

The relation between rust infection and yield ... 67

Field Trials—

Experiments with horse-drawn and power dusters ... 68
- *Methods* ... 69
- *Results* ... 69
- *General considerations* ... 75

Aeroplane dusting experiments ... 76
- *Methods* ... 77
- *Results* ... 79
- *General considerations* ... 82

V. Discussion and conclusions ... 82

VI. Summary ... 85

VII. Acknowledgments ... 86

VIII. Literature cited ... 87

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The Prevention of Cereal Rusts by the Use of Fungicidal Dusts

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I. INTRODUCTION

Cereal rust diseases cause enormous losses to small grain crops in most of the grain-growing areas of the world. In the spring wheat area of Canada and the United States destructive epidemics of rust occur during certain seasons, while other seasons are comparatively free from rust. In most years, however, rusts are a very important factor in cereal production. The economic importance of these diseases may be realized by a consideration of the persistent regularity with which they occurred in epidemic form over this area during the present century. The most destructive of the cereal rusts, black stem rust, *Puccinia graminis* Pers., was epidemic in 1904, 1911, 1916, 1920, 1923, 1925, and 1927. The worst epidemic on record occurred in 1916. Arthur (1) states that in the Upper Mississippi Valley of the United States, the loss that year on wheat alone is estimated to have reached at least $115,000,000. According to Buller (13) the loss in Western Canada for the same year amounted to 100,000,000 bushels. Bailey (5) has pointed out rust losses in Western Canada are not confined to these " rust years ". Many sections suffer to a greater or lesser extent every year. The average annual loss in the prairie provinces of Canada is estimated to be $25,000,000. Moreover, although stem rust is the most injurious of the cereal rusts, the relative importance of the leaf rusts has been greatly underestimated and only recently have the injuries which they caused been properly appreciated by agronomists and plant pathologists.

The leaf rust of wheat, *Puccinia triticina* Erikss., is most prevalent and severe in the soft red winter wheat area of the United States, and virtually every year it is an important factor in the production of soft red winter wheat. Recent studies by Mains (62, 63) on the effect of leaf rust on the yield of wheat have shown the great economic importance of this disease. The estimated total loss for the United States in the nine years 1919 to 1927, inclusive, is 108,000,000 bushels, or an average loss of 12,000,000 bushels per year.

It is generally conceded that the breeding of rust resistant varieties offers the most promising and satisfactory method of controlling rust diseases in many areas. Owing to the enormous acreage on which small grain crops are cultivated, other control methods are difficult of application. However, while the production of varieties of cereals resistant to rust presents the ideal method, a solution of the rust problem by plant breeding will probably require the work of several years. Therefore any other method of control which gave promise of immediate relief seemed to be worthy of serious attention. An investigation to determine the possibility of preventing loss from cereal rusts by one of the common methods of plant protection—the use of fungicidal dusts—was commenced in 1925. This paper presents the results of laboratory, greenhouse, and field experiments which have been carried on during the six years 1925-1930 inclusive, at the Dominion Rust Research Laboratory, Winnipeg, Man.

Presented to the Faculty of the Graduate School of the University of Minnesota as a thesis in partial fulfilment of the requirements for the degree of Doctor of Philosophy, granted December, 1931.

II. HISTORICAL REVIEW

Plant Disease Control by Dusting

It is of interest that the milestones in the development of various phases of plant disease control coincide closely with the occurrence of particular epidemics. The appearance in Europe of the powdery mildew of the vine, *Uncinula necator* (Schwein.) Burr., in 1845, was followed by the extensive use of sulphur as a fungicide; a severe outbreak in France of the downy mildew of grapes *Peronospora viticola* De Bary, in 1879, preceded Millardet's discovery of the fungicidal value of the copper sulphate-lime mixture; and the development of the lime sulphur solutions by Cordley (20), in 1907, followed closely destructive epidemics of certain fruit diseases in the United States. The enormous losses caused by the stem rust disease of wheat during the decade 1916 to 1925 instigated a more intensive study of the possibility of controlling cereal rusts by the use of dust fungicides.

The application of toxic materials in the form of a finely-divided powder was used by the Greeks and Romans, who threw ashes, lime, and other materials on plants to protect them from the ravages of disease. According to Bourcart (11), the earliest scientific use of dust fungicides was the application of sulphur to grapes in France in 1846 to control powdery mildew. Mason (66) claims that sulphur was used for the treatment of this disease in the United States as early as 1845. Lodeman (60) reports that in 1861 Millardet found a mixture of powdered iron sulphate with sulphur which arrested the development of powdery mildew. After 1846 the practise of dusting spread rapidly and considerable success was achieved in Europe in the control of many destructive diseases of the vine. With the discovery of Bordeaux mixture by Millardet (71) in 1885, and the general adoption of copper sprays, dusting was not given any particular attention.

About 1900, dusting came into favour again in North America, dusts being substituted for sprays especially for the control of apple tree diseases, and this method of control received a good deal of attention at various experimental stations. But after the development of the lime sulphur sprays by Cordley (20) in 1907, and the employment of more efficient machinery for applying sprays, dusting was again superseded by spraying as a method of controlling diseases of fruit trees.

A revival of dusting began in 1912 when extensive experiments at Cornell University were made to determine the relative effectivenes of dusting and spraying for the control of apple scab and codling moth. As a result of these investigations, considerable experimental work was resumed in many parts of the United States and Canada by Blodgett (9), Reddick and Crosby (79), Whetzel (98, 99), Sanders (83), and Doran (23). Mason (66) states that the high efficiency reached in dusting practices of to-day are almost entirely due to the efforts of these investigators.

The fungicides now most commonly employed in dusting practises fall into two large classes, sulphur and copper dusts. Sulphur has proved to be one of the most effective fungicides for the control of diseases caused by rust fungi. Doran (24) showed that copper was but slightly toxic to germinating urediniospores of various rust fungi. Butler (15), Doran (22), and Stone (90) found that sulphur controlled snapdragon rust, *Puccinia antirrhini* Diet. & Holw., and Smith (85, 86) demonstrated that this material was effective against the asparagus rust, *Puccinia asparagi* D.C., in California. Pape (74), Stewart (92), and Steinmetz (89) have used sulphur successfully in controlling carnation rust, *Uromyces dianthi* (Pers.) Niessel. Mains (61) has reported that sulphur dusting is very effective in preventing a number of the diseases of ornamentals, produced by rusts. In a recent paper Goldsworthy and Smith (30) state that sulphur

and sulphur compounds are more toxic than copper to the germinating uredinio-spores of the peach rust fungus. Sulphur compounds, in general, seem to be more toxic than copper compounds to germinating rust spores.

Sulphur as a Fungicide

The value of sulphur as a fungicide was known prior to the scientific study of the fungi against which sulphur is now used. As early as 1821, before there was accurate knowledge of the disease, Robertson (81) found that sulphur mixed with soap suds was a specific remedy for the treatment of mildew of peaches. According to Lodeman (60), the earliest lime sulphur solutions were those prepared by Kendrick in 1833, by Guisan in 1851, and by Regel in 1854. All of these, however, were used as disinfectants.

Bourcart (11) states that the fungicidal properties of sulphur dust were first discovered by a French gardener, Kyle, in 1846, in some greenhouse experiments with lime and sulphur. Its use was greatly stimulated by the destructive outbreak in France of the powdery mildew diseases. In 1848, Duchartre, then Professor of Botany at the Agronomical Institute of Versailles, recommended the use of sulphur against the fungus. Its employment met with such success that sulphur became the greatest factor in the control of many powdery mildew diseases. It is interesting to know that sulphur is still the leading dust fungicide.

Sulphur itself is generally employed as a dust. Until recently the finely-divided flowers of sulphur was deemed especially suitable for dusting purposes. With the advent of better machinery a ground sulphur of greater fineness was produced. To this product the name of flowers of sulphur also has been applied, although perhaps the designation " flour sulphur " is more appropriate. In addition to these two forms, sublimed and ground sulphur, there are sulphur-containing refuse products which have been utilized for dusting purposes. Green sulphurs are formed from certain coal-gas purifications. Martin (65) states that the recovery of sulphur from alkali waste is another process. Sulphur precipitated in this way is too expensive for general use as a fungicide. Upon the relative merits of these different forms of sulphur for controlling plant diseases little can be said except that the degree of fineness is important.

A number of hypotheses have been advanced to explain the manner in which sulphur acts on the fungus. The earliest views have been summarized by Windisch (102). This writer points out that the physical properties may play some part. Mangini, in 1871, considered that the electricity produced by the contact of the plant and the sulphur particle might prove toxic to the fungus. In 1874, Mach suggested an optical action, the fine sulphur particles forming small lenses which, focusing the sun's rays on the fungus, kill it by heat. In 1875, Pollacci (77) observing that, in the presence of sulphur, certain yeasts and moulds produce sulphuretted hydrogen, suggested that this gas was the toxic agent. Reviews of the earlier work on this topic have been given by Windisch (102), Barker Gimingham, and Wiltshire (6), Doran (23), Young (104), Vogt (96), Tisdale (95), Thatcher and Streeter (94), Goodwin and Martin (31), and others. There is a great diversity of opinion expressed and much of the earlier work is inconclusive and not supported by experimental evidence.

In recent years the fungicidal action of sulphur has been the subject of numerous investigations, and a voluminous literature has accumulated. Barker (7, 8), Martin (65), Young and Williams (101, 105, 106), Goodwin and Martin (32), March (64), Young (107), Goodwin (33), Salmon et al (82), Goodwin, Martin, and Salmon (34), and Wilcoxon and McCallan (100), have published detailed statements of their results. There is still conflict of opinion as to how the fungicidal action of sulphur is exerted. Although the toxic action of sulphur has been attributed to practically every compound that

might conceivably be formed from the element, the compounds now most commonly investigated are volatilized sulphur, sulphur dioxide, sulphur trioxide, hydrogen, sulphide, and pentathionic acid.

Some workers maintain that the element itself is the active agent, either in the finely-divided form or as a vapour, although its low solubility and low vapour pressure have led the majority to consider it rather as a source of some more toxic principle. Recent studies by McCallan (68), Liming and Young (58), Liming (59), and McCallan and Wilcoxon (69) have indicated that the toxic action may be governed by the condition of the fungus rather than by the condition of the active principle. McCallan and Wilcoxon (69), believe that the reaction is dependent on reducing enzymes secreted by the living cell, with hydrogen sulphide as a final product.

The Prevention of Cereal Rusts by the Use of Chemicals

Considerable work has been done in endeavours to prevent attacks of cereal rusts by chemical means. As early as 1888 Kellerman (48) treated wheat, oats, and barley with flowers of sulphur, potassium sulphide, chloride of iron, and Bordeaux mixture, but with negative results. Pammel (73) found that the application of ammoniacal carbonate of copper and Bordeaux mixture were entirely useless in preventing rust. Hitchcock and Carleton (44, 45) made experiments with fungicides in an effort to prevent rusts of barley and oats. Their results were not conclusive, although they cannot be looked upon as indicating entire failure. Many investigators, including Bolley (10), Cobb (19), Galloway (28), Pearson (75) and Noiret (72), used fungicides on growing plants to ascertain whether or not the development of rust could be prevented.

The possibility of controlling rusts by the use of chemicals was discussed by Eriksson and Henning (25), who give a detailed summary of the earlier investigations and conclude that, although partial control of rust is possible by the use of fungicides, practical control is not feasible. For many years, then, it was assumed that cereal rusts could not be controlled effectively and practically by either spraying or dusting. Dusting seemed to be quite ineffective and, owing to the enormous acreage on which small grain crops are cultivated, spraying seemed to be entirely impractical.

The enormous losses caused by cereal rust diseases in the spring-wheat region of Canada and the United States during the decade 1916-1925; the development of improved fungicidal dusts; and the difficulties and uncertainties which have surrounded the production of rust resistant varieties, have given considerable impetus to the possibility of dusting as a means of combating these diseases. In 1924, Kightlinger (49) undertook some experimental work on dusting oats for the control of rust. The results of his experiments were extremely suggestive, and they demonstrated clearly the possibility of controlling cereal rusts by dusting growing plants with sulphur. Kightlinger pointed out, too, that while in its broader aspects the problem of controlling cereal rusts by chemical means involves the use of fungicidal protectants in any form, spraying has to be excluded because of its obvious impracticability. Eriksson and Henning (25), Lambert and Stakman (54), and Gassner and Straib (29) recognized the impracticability of spraying for the control of rust diseases of small grains.

Bailey and Greaney (2), in 1925, obtained evidence to show that both leaf rust and stem rust of wheat may be effectively controlled, even under severe natural epidemic conditions in the field, by dusting the standing crop with sulphur. In 1926, Kightlinger and Whetzel (50), and Lambert and Stakman (53), reported evidence in support of Kightlinger's earlier statement that sulphur controls rust under certain conditions. In 1927, Bailey and Greaney (3) published the results of small plot experiments in which sulphur was applied by means of a hand duster, as well as field experiments in which the sulphur was applied by means of horse-drawn dusters. The same investigators (4), in 1928, reported successful

results in small plot experiments and in some instances where wheat, under ordinary field conditions, was dusted both by horse-drawn dusters and by aeroplane.

Hermannes (42), Siblia (84), Petri (76), Lambert and Stakman (54), Broadfoot (12), and Greaney (38, 39) have published results of dusting experiments for the control of cereal rusts. Mains (62), in 1927, found that leaf rust of wheat (*Puccinia triticina*) was greatly reduced in field plots by dusting them with sulphur. According to Melchers (70) dusting wheat with sulphur prevented the development of leaf rust, both in the greenhouse and field. The recent results obtained by Gassner and Straib (29) in the control of leaf rust and stripe rust of wheat (*Puccinia triticina* and *Puccinia glumarum*) and of leaf rust of rye (*Puccinia dispersa*) by chemical methods are of considerable interest. These workers question the practicability of using sulphur for the control of rust. They consider, however, that for the purpose calcium cyanamide holds decidedly better possibilities. Stakman and Person (88) have recently given a popular account of wheat dusting experiments carried out in Minnesota in 1925, 1926, and 1927. A recent publication by Greaney (40) gives a practical account of dusting grain plots with sulphur for the control of rust.

III. OBJECTS OF INVESTIGATION

The principal objects of the present investigation were to determine: (1) whether or not cereal rusts could be effectively prevented by fungicidal dusts, and (2) how practical this method of prevention might be. The experimental phases of the investigation consisted of laboratory, greenhouse, and field studies.

The purpose of the laboratory studies was to compare the susceptibility of several cereal rust fungi to sulphur and copper dusts, and to study some of the factors influencing their fungicidal activity. Numerous tests were made on the inhibitory effects of fungicidal and inert dusts on the germination of aeciospores and urediniospores.

Dusting tests in the greenhouse on growing plants were employed to ascertain the relative value of various fungicidal dusts and to study some of the most important factors influencing their effectiveness. The difficulties involved in ascertaining the requirements of a good protectant under more or less unnatural conditions in the greenhouse, emphasized the importance of using dusting experiments on a large scale under actual field conditions to serve as the final test in the evaluation of dust fungicides.

Extensive field experiments were therefore made to study such factors as toxicity to the plant, adhesiveness, as well as certain principles relative to the effectiveness and practical value of dusting for the prevention of cereal rusts.

During the course of the investigation three types of field experiments were made. (1) Small plot experiments were used to study the fungicidal effectiveness of various dusts and to determine the most satisfactory rate of dust application; the most suitable interval between dustings; the time at which dusting should be begun; the least number of applications that will control rust; the relative value of different methods of dust application; and the influence on the effectiveness of dust treatments, at the time of and subsequent to dusting, of different meteorological factors. The data accruing from many of the small plot experiments were used to study the effect of rust infection on the yield of cereal crops. (2) Field trials with horse-drawn and power dusters were employed to devise practical dusting schedules for rust control. (3) Aeroplane dusting experiments were made to determine the practical utility of the aeroplane for dusting; to develop an efficient technique for dusting large fields; and to study the influence of different rates of application, the most satisfactory interval between dustings, and timeliness of dust application.

It seemed essential that data be collected over a period of years before a correct evaluation of dusting for the control of cereal rusts could be made. Some of the field experiments have been carried on for as long as six years, 1925 to 1930, inclusive.

IV. EXPERIMENTAL WORK

A. Laboratory Studies

In the preparation and selection of fungicides, laboratory tests to determine their toxicity is of primary importance. In the present studies spore-germination tests have been made to determine the toxicity of various copper, sulphur, and inert dusts to cereal rust fungi.

MATERIALS AND METHODS

In both laboratory and greenhouse studies the following fungicides were used: sulphur dust of various kinds, copper sulphate-lime dust (Niagara dust D-6 with copper as metallic copper, 6·8 per cent), copper carbonate dust, (Corona dust with not less than 13 per cent copper as metallic copper), and various oxidized sulphur dusts. In addition, a number of finely-divided inert dusts were used in compartive tests with sulphur dusts. Kolodust (Niagara colloidal sulphur dust) was used as the standard sulphur dust. The degree of sensitivity of spores of the following cereal rust fungi to dust fungicides was studied: Aeciospores of *Puccinia graminis tritici* Erikss, and Henn., and *Puccinia graminis agrostis* Erikss. and Henn., and urediniospores of *Puccinia graminis avenae* Erikss, and Henn., *Puccinia graminis tritici* Erikss, and Henn., *Puccinia triticina* Erikss., *Puccinia coronata avenae* Erikss. and Henn., *Puccinia anomala* Rostr., and *Puccinia glumarum* (Schm.) Erikss. and Henn.

The fungi used in both laboratory and greenhouse tests were collected in Western Canada, and were cultured and identified by Dr. Margaret Newton, Dr. T. Johnson, and Mr. A. M. Brown, at the Dominion Rust Research Laboratory, Winnipeg, Man. Aeciospores from uniformly matured aecia and urediniospores of definite physiologic forms of stem rust were used. Only physiologic forms that were constant in their reaction on the differential hosts were made use of in the tests.

The methods followed were those described in previous experiments (38), and consisted essentially of germinating the spores in drops of water on glass slides placed on small blocks in inverted petri dishes used as moist chambers, two slides being placed in each dish. The slides were first dusted, and then an aqueous suspension of spores was pipetted onto them. Two drops were placed on each slide, and twelve slides in six moist chambers constituted a complete set.

Petri dishes containing undusted slides with an aqueous suspension of spores in drops on each slide served as controls. Several fungicides were tested at one time. The methods followed were very similar to those devised by Reddick and Wallace (80). These methods have been modified and described in detail by McCallan (67). The practicability, advantages, limitations, and uses of laboratory tests of fungicides have been discussed by Wallace, Blodgett and Hesler (97) and by McCallan (67).

The spore suspensions were made by washing the spores from the natural substrate with distilled water and filtering the resulting solution through cheese-cloth to remove clumps of spores and pieces of substrate. The spore concentrations of the aqueous suspension were regulated by dilution until, as ascertained by examination under the miscroscope, approximately twenty-five spores were found in a low power field of 1·45 mm. diameter. In the determination of the toxicity of a given dust fungicide to a given fungus, the number of spores per field was always approximately the same.

The moist chambers were maintained at optimum temperatures for the germination of the spores. Urediniospores of *P. glumarum* were germinated at a temperature range of 8° to 10° C. The temperature for aeciospores and urediniospores of the other fungi was within the range of 14° to 20° C. Doran (21) states that a fungicide cannot be considered toxic unless it is toxic under optimum conditions for spore germination. In toxicity tests with various fungi, he found that when the temperature was near the maximum or minimum for germination of the spores some fungicides were toxic that were not toxic at optimum temperatures. Clark (16) concluded also that a fungus is most resistant to the action of the fungicide when the temperature is at the optimum for germination.

The time allowed for germination before examination was from 18 to 24 hours. The method employed in expresisng the toxicity of a fungicide was merely to record the percentage of germinated spores. Absolute germination percentages were recorded. No detailed records were made of the length and character of the germ tube. It was assumed that any spore possessing a germ tube longer than twice the length of the spore had germinated and was capable of producing infection, although from observations made on growing plants in the greenhouse, it is doubtful whether or not all the spores recorded as having germinated in the laboratory tests would be capable of producing infection.

Experiments in which the germination of the spores on the control slides showed poor viability were disregarded as untrustworthy. In general, four microscopic fields were examined in each spore-suspension drop, but, in the case of low spore-suspension concentrations, more fields were examined. From 1,000 to 1,200 spores were counted from the ten or twelve slides of each test. All the tests were repeated from four to six times. Although the experimental data were not studied statistically it was realized that the larger the number of spores counted the smaller would be the significant difference between various treatments.

EXPERIMENTAL RESULTS

Relative Toxicity of Sulphur and Copper Dusts

The results in Table 1 show the effect of copper and sulphur dusts on the aeciospores of two varieties of *P. graminis*. It can readily be seen that these spores are very sensitive to sulphur and copper. The average percentage germination of aeciospores tested on slides dusted with these materials was exceedingly low. The germination percentage in the controls is not high, and although this may be considered a fairly good germination with spores which are as variable in their germinability as aeciospores of *P. graminis,* the percentage is lower in the treated spores. For this reason, therefore, the results are only indicative of the actual toxicity of these dusts to aeciospores. Figure 1 illustrates the effect of copper and sulphur dusts on the germination of these spores.

TABLE 1.—Relative toxicity of sulphur and copper dusts to the aeciospores of *Puccinia graminis* (Temperature 14°—16° C.)

Fungus	Fungicide	Per cent germination*					
		Test 1	Test 2	Test 3	Test 4	Test 5	Aver.
P. graminis agrostis	Sulphur (Kolodust)	0·1	0·2	1·3	0·8	0·3	0·3
	Copper dust (Sulphate-lime)	0·5	0·8	2·1	2·4	0·6	1·3
	Control	11·6	22·0	44·7	16·3	20·6	23·0
P. graminis tritici	Sulphur (Kolodust)	0·3	1·0	0·4	0·4	0·9	0·6
	Copper dust (Sulphate-lime)	1·5	0·1	0·4	1·0	0·9	0·8
	Control	38·3	26·1	27·1	32·4	23·9	29·6

*Each test represents the absolute germination percentage in a count of 1,000 spores.

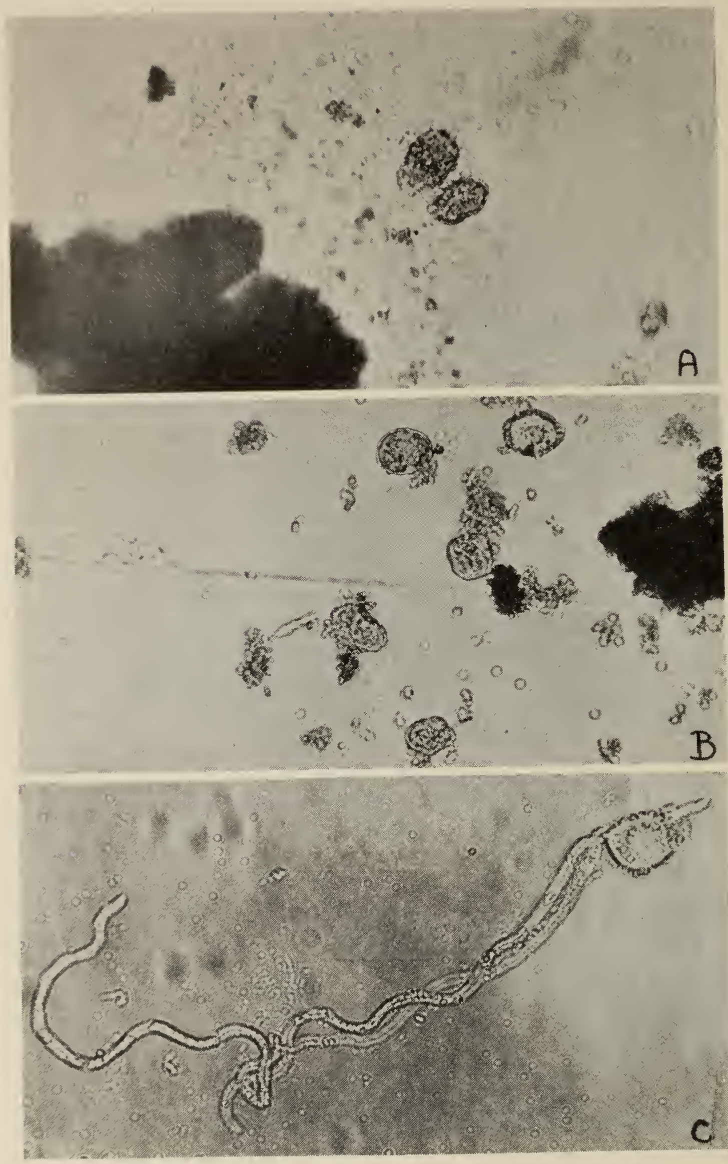

Fig. 1.—Effect of copper and sulphur dusts on the germination of aeciospores of stem rust of wheat—*Puccinia graminis tritici*. A. Spores on glass slide treated with sulphur (Kolodust). No germination. B. Spores on glass slide treated with copper lime dust. Note disintegration of short germ tubes. C. Control, not treated with dust. Germinating aeciospore in suspension-drop on glass slide.

Sulphur appeared to be slightly more toxic than copper. Doran (24), testing aeciospores of various rust fungi, showed that these, as a rule, were resistant to copper. He found, however, that no spores germinated in copper sulphate solutions containing 0·127 per cent copper. Recent investigations by McCallan (68) have indicated that the toxicity of copper is dependent not only on the total amount of copper present but also to a certain extent on the rate of diffusion of the copper ions. He suggests that spore excretions are the chief agency in bringing about the liberation of copper from insoluble copper protectants. An interesting point in the present experiments is the extreme toxicity of sulphur to the aeciospores of the stem rust fungus.

TABLE 2.—Relative toxicity of sulphur and copper dusts to the urediniospores of *Puccinia graminis*. (Temperature 18°—20° C.)

Fungus	Fungicide	Per cent germination				
		Test 1	Test 2	Test 3	Test 4	Aver.
P. graminis tritici	Sulphur (Kolodust)	4·6	2·7	3·2	3·5	3·5
	Sulphur (Electric)	10·3	3·1	6·6	4·0	6·0
	Copper dust (Carbonate)	2·2	0·5	1·0	1·2	1·2
	Copper dust (Sulphate-lime)	0·6	0·2	1·3	0·8	0·7
	Control	91·6	64·8	95·5	91·8	85·9
P. graminis avenae	Sulphur (Kolodust)	8·4	3·0	2·4	3·2	4·2
	Sulphur (Electric)	7·1	1·1	3·9	2·3	3·6
	Copper dust (Carbonate)	1·1	0·7	0·6	0·8	0·8
	Copper dust (Sulphate-lime)	0·6	0·0	0·3	0·1	0·2
	Control	96·3	63·8	76·4	78·9	78·8

In tables 2 and 3 are recorded the germination percentages of urediniospores of some leaf rusts and stem rusts of cereals. The results of these tests are in very close agreement, and indicate the extreme toxicity of copper dusts to urediniospores. Doran (24) showed that the average lethal concentration in per cent copper for aeciospores is three times as great as for urediniospores of rust fungi. In these experiments aeciospores are not more sensitive to copper dusts than urediniospores. Figures 2 and 3 show the effect of sulphur and copper dusts on the germination of urediniospores of leaf rust and stem rust of wheat.

TABLE 3.—Relative toxicity of sulphur and copper dusts to the urediniospores of *Puccinia triticina*, *Puccinia coronata*, *Puccinia anomala*, and *Puccinia glumarum*.

Fungicide	Per cent germination*			
	Puccinia triticina	Puccinia coronata	Puccinia anomala	Puccinia glumarum
Kolodust (sulphur)	6·9	4·8	6·1	0·0
Electric sulphur	9·4	6·3	8·3	0·2
Copper carbonate dust	1·1	0·4	0·7	0·0
Copper sulphate-lime dust	0·2	0·1	0·3	0·0
Control	86·3	96·5	90·6	64·6

*Average results of four tests run at different times. Absolute germination percentage in count of 4,000 spores.

Doran (24), Butler (14), Smith (85, 86), Goldsworthy and Smith (30), and Mains (61) have shown that, in general, urediniospores of rust fungi are more resistant to the action of copper than are other fungi, and that they are fairly susceptible to sulphur. Doran (22) reported that dry urediniospores of *Puccinia anterrhini* mixed with powdered sulphur and kept 3½ hours at a temperature of 21° C., did not germinate. From the results given in table 2 and 3 it would

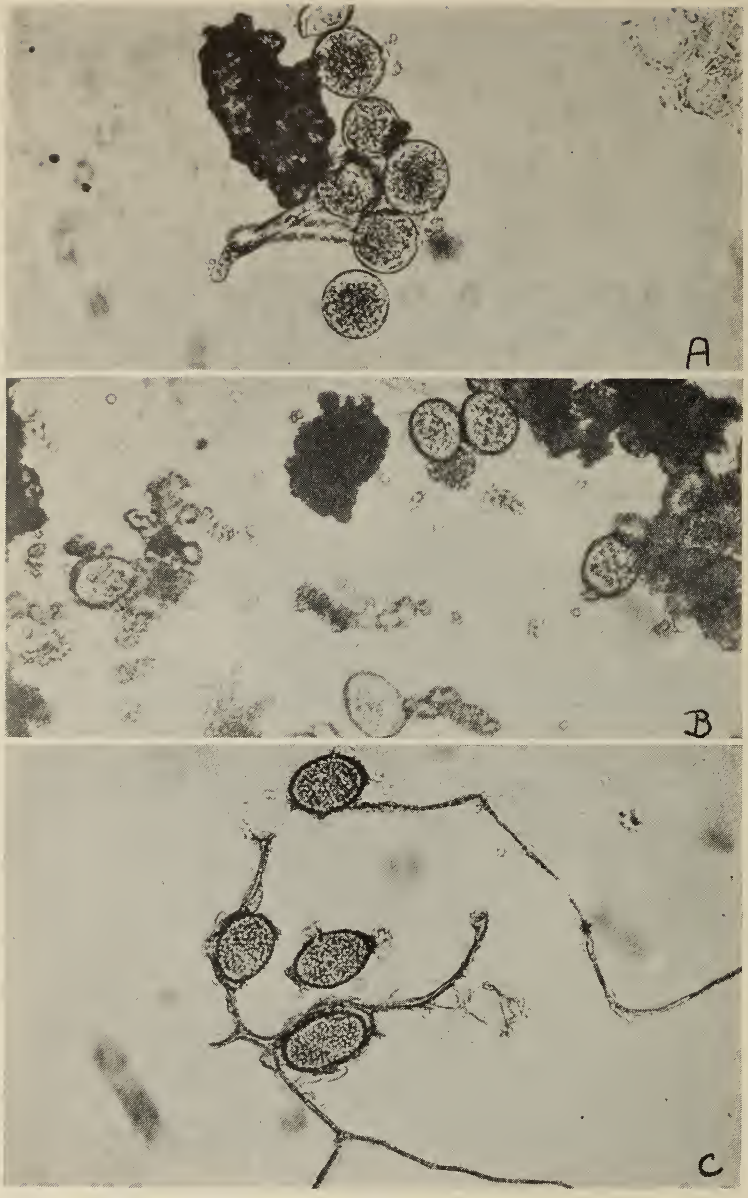

Fig. 2.—Effect of sulphur and copper dusts on the germination of urediniospores of leaf rust of wheat, *Puccinia triticina*. A. Spores on glass slide treated with sulphur (Kolodust). Germination is slight and the germ tubes short and stunted. B. Spores on glass slide treated with copper sulphate-lime dust. Few short distorted germ tubes. C. Control, not treated. Spores in suspension-drop on glass slide germinating vigorously.

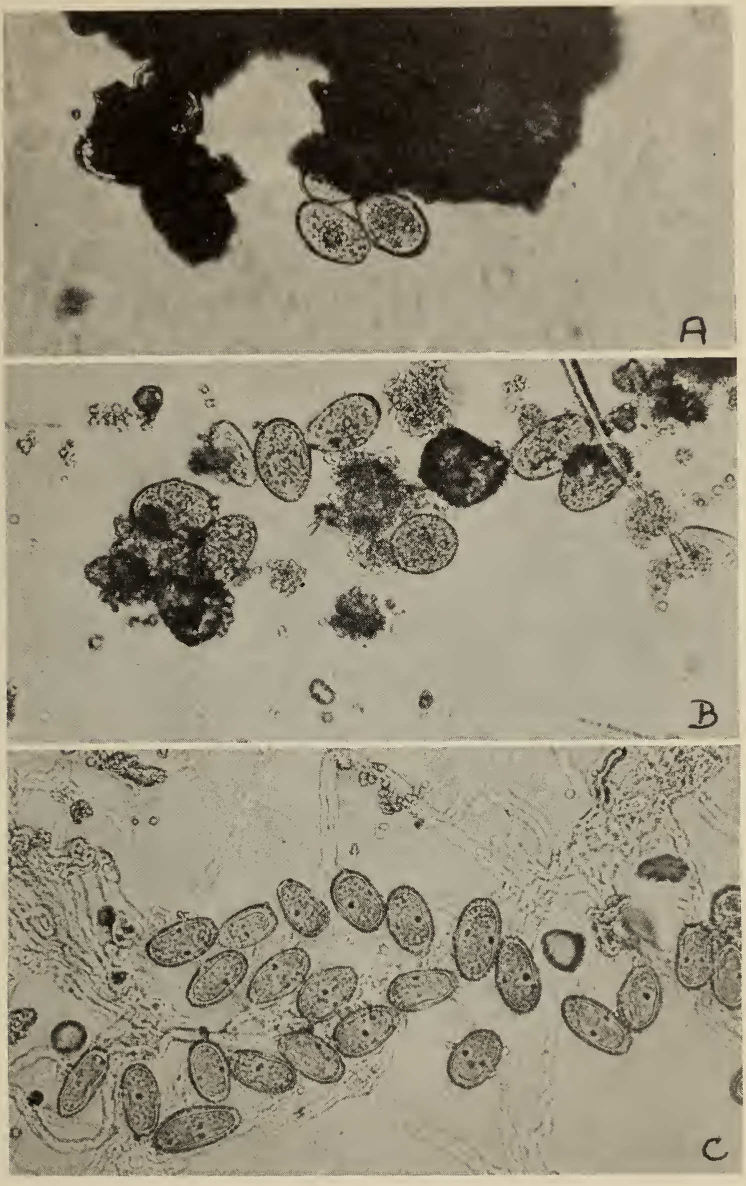

FIG. 3.—Effect of sulphur and copper dusts on the germination of urediniospores of stem rust of wheat—*Puccinia graminis tritici*. A. Spores on slides treated with sulphur (Kolodust). B. Spores on slide treated with copper sulphate-lime dust. C. Control, slide not dusted.

seem that sulphur will largely prevent the germination of urediniospores of cereal rusts. Kolodust was slightly more effective than Electric sulphur in reducing germination.

The stripe rust fungus, *P. glumarum,* was very sensitive to sulphur. The toxicity of sulphur at a temperature ranging from 10°-12° C., the optimum temperature for the germination of urediniospores of this rust, indicates that sulphur acts at fairly low temperatures.

Toxicity of Various Sulphur Dusts

Powdered sulphur has been extensively used in the control of fungi, especially mildews and rusts. Young (104), Thatcher and Streeter (94), Streeter and Rankin (91) and Wilcoxon and McCallan (100) regarded the degrees of fineness of sulphur as an important factor in determining its effectiveness as a fungicide. In the present experiments the size of the particles was considered as a factor that might influence the toxicity of sulphur to spores of cereal rust fungi.

TABLE 4.—Toxicity of various sulphur dusts to the germination of urediniospores of *Puccinia graminis.* (Temperature 18°—21° C.)

Fungus	Fungicide	Per cent germination					
		Test 1	Test 2	Test 3	Test 4	Test 5	Average
P. graminis tritici	Bentonite-sulphur	0·5	0·4	0·5	0·1	0·6	0·4
	Kolodust	2·3	1·0	0·4	1·1	0·9	1·1
	Sulfodust	2·8	3·1	3·0	4·5	2·2	3·1
	Sulphur (300-mesh)	4·1	4·2	3·4	2·6	3·5	3·6
	Flowers of Sulphur	5·8	6·4	8·3	3·0	10·2	6·7
	Sulphur (200-mesh)	15·6	18·2	6·1	17·5	10·0	13·5
	Control	91·0	92·4	67·2	89·1	90·8	86·1
P. graminis avenae	Bentonite-sulphur	0·4	0·5	0·6	0·4	0·6	0·5
	Kolodust	2·1	0·7	0·6	3·3	1·1	1·6
	Sulphur (300-mesh)	3·5	6·6	4·7	3·8	4·9	4·7
	Sulfodust	3·2	7·0	3·1	4·5	6·1	4·8
	Flowers of Sulphur	5·8	9·0	6·3	9·0	8·1	7·6
	Sulphur (200-mesh)	24·0	15·2	9·6	18·2	17·5	16·9
	Control	89·3	87·5	58·7	89·0	91·0	83·1

Kolodust, Bentonite-sulphur*, Sulfodust, Sulphur 200-mesh, Sulphur 300-mesh, and Flowers of Sulphur were examined under the microscope to determine the fineness of the particles. The order of their fineness is as follows: Bentonite-sulphur, Kolodust, Sulfodust, Sulphur 300-mesh, Flowers of Sulphur, and Sulphur 200-mesh. The toxicity of these materials to the urediniospores of *Puccinia graminis* were tested in the laboratory. From the data in table 4 it will be seen that the toxicity of sulphur increased to a marked degree with decrease in size of the particles.

Toxicity of Oxidized Sulphur Dusts

Several oxidized sulphur dusts were compared and an attempt was made to determine their effect on the germination of urediniospores. Potassium permanganate ($KMnO_4$), ground to 300-mesh fineness, was mixed with sulphur in concentrations of 1, 5, and 10 per cent. Laboratory germination tests were made with *Puccinia graminis* as the test object. Five tests were run at different times.

The results, presented in table 5, show that oxidized Kolodust and ordinary 300-mesh sulphur were toxic to a marked degree. The presence of one per cent potassium permanganate increased the toxicity of both dusts; the addition of 5 per cent increased its effect to a slightly greater extent; while sulphur dusts containing 10 per cent potassium permanganate almost completely inhibited germination. The differences between the 5 and 10 per cent oxidized dusts are, however, not significant.

* Niagara colloidal base, the active ingredient is bentonite-sulphur.

TABLE 5.—Toxicity of various oxidized sulphur dusts to urediniospores of *Puccinia graminis tritici*.

Fungicide	Concentration of $KMnO_4$ in per cent	Per cent germination					
		Test 1	Test 2	Test 3	Test 4	Test 5	Aver.
Sulphur	0	2·6	3·8	3·1	3·1	5·2	3·6
"	1	0·2	0·1	1·0	0·4	0·8	0·5
"	5	0·1	0·0	0·1	0·2	0·2	0·1
"	10	0·0	0·0	0·0	0·0	0·0	0·0
Control	0	92·1	80·0	87·5	54·3	76·5	78·1
Kolodust	0	0·5	0·4	1·0	0·9	1·7	0·9
"	1	0·0	0·2	0·1	0·2	0·3	0·2
"	5	0·0	0·0	0·0	0·2	0·1	0·1
"	10	0·0	0·1	0·1	0·0	0·1	0·1
Control	0	91·3	90·0	87·0	64·9	83·5	83·3

Relative Toxicity of Inert and Sulphur Dusts

Previous experiments have indicated that certain physical qualities might be correlated with the fungicidal activity of sulphur dust. Furthermore, it has just been shown that the toxicity of sulphur increases to a marked degree with decrease in particle size. If an oxidation product of sulphur is the toxic principle, the more rapid oxidation of the small particles into toxic substances may probably partially account for the increased fungicidal action of the more finely-divided dusts. It may possibly be, however, that the dust particle itself is toxic to the germination of the spore.

In order to determine the effect of the physical qualities of dust particles on the germination of spores, a number of inert dusts were used in comparison with Kolodust and Sulfodust in some germination tests. The size of the particles of the inert dusts was approximately the same as that of Sulfodust. Urediniospores of *P. graminis tritici*, *P. graminis avenae*, and *P. triticina* were used as test objects.

TABLE 6.—Relative toxicity of various inert and sulphur dusts to the germination of urediniospores of *Puccinia graminis tritici*, *Puccinia graminis avenae*, and *Puccinia triticina*.

Fungus	Dust	Per cent germination						
		Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Average
P. graminis tritici	Kolodust	·6	1·1	·8	1·4	·4	·5	·8
	Sulfodust	2·5	4·3	5·1	4·0	2·8	6·6	4·2
	Chalk	87	91	72	91	92	90	87·1
	China Clay	92	90	76	93	91	89	88·5
	Talc	86	89	81	88	89	92	87·5
	Control	81	90	78	92	87	88	86·0
P. graminis avenae	Kolodust	·4	·2	2·2	1·0	1·4	·3	·9
	Sulfodust	1·8	1·1	5·0	4·3	5·5	1·5	3·2
	Chalk	86	75	92	90	76	74	82·1
	China Clay	82	61	94	90	60	88	79·1
	Talc	78	72	89	87	68	87	80·1
	Control	78	71	96	94	68	83	81·7
P. triticina	Kolodust	1·6	·8	·3	·6	1·1	·8	·9
	Sulfodust	2·6	3	1·1	2·1	2·1	3·1	2·3
	Chalk	61	85	85	39	75	81	71·0
	China Clay	76	83	85	63	73	80	76·7
	Talc	85	86	89	53	73	78	77·3
	Control	96	76	93	54	70	76	77·5

The results are given in table 6. The inert dusts, talc ($H_2Mg_3Si_4O_{12}$), china clay ($H_4Al_2Si_2O_9$), and chalk ($CaCO_3$), showed no toxic action towards the urediniospores of rust fungi. There was no marked reduction in the percentage of spore germination as compared with the control cultures. In these tests, Kolodust and Sulfodust were decidedly toxic to the urediniospores of leaf and stem rusts.

B. Greenhouse Studies

The toxicity of a fungicide having been determined in the laboratory, it was then possible by greenhouse tests to study such factors as adhesiveness, toxicity to the plant, and actual fungicidal efficiency. The fungicidal relationship involves essentially, in cereal rust control, a relationship of fungus spore and protectant. Greenhouse tests on growing plants confined to this relationship, then, may be expected to be both reliable and practicable. The advantage of these tests lies in the saving of time, expense, and labour, and in a more definite control of environmental conditions. It is realized, however, that practical dusting experiments under natural field conditions must serve as the final test in the evaluation of the effectiveness and practicability of a fungicide for the control of rust.

Dusting tests were made to study the relative fungicidal value of various copper and sulphur dusts, to study the comparative effectiveness of various commercial dusting sulphurs, and to ascertain whether or not the fungicidal activity could be increased by the addition of oxidizing agents to sulphur. An attempt was made also to study some of the factors influencing the fungicidal effectiveness of sulphur.

MATERIALS AND METHODS

Dusting tests were carried on in the greenhouse under conditions which simulated as far as possible actual field conditions. Conditions for rust infection and the factors relative thereto, such as susceptible hosts, amount, source, and age of inoculum, method of inoculation, application of fungicide, temperature, light, and time, were standardized in each experiment. The larger part of the work was conducted with *P. graminis*, both wheat and oat forms of this rust being used as test objects. Tests were made also with *P. triticina, P. glumarum, P. coronata avenae,* and *P. anomala.*

Seedlings were grown in 5-inch pots, 10 to 12 plants in each pot. Ten days after planting, when the first leaves were from 8 to 10 centimetres long, the plants were ready for use. In some experiments they were inoculated just before, and, in others, immediately after dust application. The fungicide to be tested was applied with the same duster with which the slides in the laboratory studies had been dusted so that the applications on leaves and slides were approximately equal as to amounts per unit area.

In most of the experiments the plants were inoculated immediately following dust application. Urediniospores and aeciospores from cultures maintained for the purpose of the investigation were used. Suspensions of spores in distilled water were applied with an atomizer. Where the plants were inoculated before the dust was applied, they were moistened and urediniospores were applied to the lower leaves by means of a small scalpel. In each experimental test a definite physiologic form of rust was used.

The inoculated plants were incubated in moist chambers for 48 hours at the optimum temperature for spore germination. In order to avoid any effect from volatile substances, separate chambers were utilized for each set of dusted and undusted plants. After the plants had been taken from the incubation chambers, they were placed on greenhouse benches where they were kept under uniform

conditions of light, humidity, and temperature. Wherever the methods of inoculation and dust application were modified the modifications are given in detail with the results of the experiment.

In any given experiment, approximately one hundred plants were used for each treatment. The controls consisted of an equal number of inoculated but undusted plants. As it is almost imposible to regulate all the conditions surrounding the testing of fungicides in the greenhouse, a repetition of the experiments seemed desirable. In these studies, therefore, tests were run at different times, the average of two or more tests being used to express the effects of any given treatment.

Observations on the number of plants infected, the degree of rust infection, and the adherence and toxicity of the fungicide to the plant were recorded twelve to sixteen days after inoculation. The percentage of plants infected and the degree of infection were the criteria upon which the effects of the various treatments were based. Absolute infection percentages were recorded not relative percentages; that is, the controls were not raised to the basis of 100 and the other readings adjusted in proportion. The method employed did not mask the variation between treatments, and it was possible to make true comparisons. The plants were examined, but not classified, individually. The degree of rust infection recorded in the experimental data is the average for all plants in the test. The basis of classification will be clear from table 7.

TABLE 7.—Explanation of symbols used to indicate degrees of rust infection in greenhouse dusting tests.

(−)	Trace.—Uredinia isolated, few in number; usually at tip of leaf.
±	Light.—Uredinia isolated; covering a limited surface of the leaf.
+	Moderate.—Uredinia fairly numerous; scattered over leaf surface. Degree of infection variable.
++	Severe.—Uredinia abundant; covering a large area of the leaf surface.

EXPERIMENTAL RESULTS

Relative Fungicidal Value of Sulphur and Copper Dusts

Sulphur and dehydrated copper sulphate are the dust fungicides most commonly used at the present time. In Canada and the United States, sulphur is used almost exclusively for the control of diseases of fruit trees, while in some of the cooler latitudes copper dusts have given satisfactory results. A recently developed fungicide, copper sulphate-lime dust, was first used by Sanders (83) in Nova Scotia, where it gave considerable promise for the control of apple scab. A number of greenhouse experiments were made in which several dust fungicides were tested. The results of dusting tests in which wheat plants were inoculated with aeciospores of *P. graminis tritici* are given in

TABLE 8.—Fungicidal value of sulphur and copper dusts. Dusting tests with aeciospores of *Puccinia graminis tritici*.

Fungicide	Percentage of Marquis wheat plants infected			
	Test 1	Test 2	Test 3	Average
Kolodust (sulphur)	0·0	1·2	0·6	0·6
Electric sulphur	2·4	1·6	1·1	1·7
Copper sulphate-lime dust	21·0	11·3	18·6	17·0
Copper carbonate dust	19·3	21·8	30·3	23·8
Check (no dust)	38·1	32·8	57·3	42·7

table 8, (Fig. 4). The results of studies with urediniospores of *P. graminis tritici* and *P. graminis avenae* are presented in table 9, while the results with urediniospores of *P. triticina, P. coronata, P. anomala* and *P. glumarum* are brought together in table 10. Figures 5, 6 and 7 illustrate the relative effect of sulphur and copper dusts on the degrees of infection by urediniospores of cereal rusts.

The results in tables 8, 9, and 10 are in very close agreement and indicate the extreme toxicity of sulphur to aeciospores and urediniospores of cereal rusts.

TABLE 9.—Fungicidal effectiveness of sulphur and copper dusts. Dusting tests with urediniospores of *Puccinia graminis tritici* and *Puccinia graminis avenae*. (Average of four tests).

Fungicide	*Puccinia graminis tritici*			*Puccinia graminis avenae*		
	Per cent of plants infected	Degree of in-fection	Toxicity to plants	Per cent of plants infected	Degree of in-fection	Toxicity to plants
Sulphur (Kolodust)	0·0	0	0	2·7	(−)	0
Sulphur (Electric)	1·2	(−)	0	9·0	±	0
Copper dust (Sulphate-lime)	24·2	+	severe	48·8	+	slight
Copper dust (Carbonate)	32·1	+	severe	73·5	+	slight
Check (no dust)	100·0	++	0	100·0	++	0

Almost complete inhidition of aeciospore and urediniospore germination was affected by copper dusts in the laboratory, but in the greenhouse tests they were not so effective. On the other hand, while sulphur dusts were not nearly so effective as copper dusts in the laboratory, very excellent results were obtained in the greenhouse on growing plants. The use of copper dusts for the prevention of infection by urediniospores and aeciospores of rusts is probably impractical owing to the cost of these materials. The indications are that sulphur dusts are very toxic to the germination of rust spores and might be very effective in reducing infection in the field. Butler (14) found copper sulphate solutions containing 0·25 per cent copper sulphate, toxic to the foliage of tomatoes, beans,

TABLE 10.—Fungicidal effectiveness of sulphur and copper dusts. Dusting tests with urediniospores of *Puccinia triticina, Puccinia coronata, Puccinia anomala*, and *Puccinia glumarum*. (Average of four tests).

Fungicide	*Puccinia triticina*		*Puccinia coronata*		*Puccinia anomala*		*Puccinia glumarum*	
	Per cent infection	Degree of infection	Per cent infection	Degree of infection	Per cent infection	Degree of infection	Per cent infection	Degree of infection
Kolodust (sulphur)	4·4	(−)	2·0	(−)	0·6	(−)	0	0
Electric sulphur	15·6	±	2·4	(−)	7·6	±	1·1	(−)
Copper sulphate-lime dust	29·2	+	27·5	±	52·1	+	3·0	(−)
Copper carbonate dust	65·2	+	79·0	+	52·8	+	5·7	±
Check (no dust)	100·0	++	100·0	++	100·0	++	69·1	+

and other plants. In the present greenhouse tests with growing plants, copper sulphate-lime and copper carbonate dusts were toxic to the young leaves of wheat, oats, and barley. Goldsworthy and Smith (30), in their studies on the peach rust fungus, have reported that almost complete inhibition of urediniospore germination was effected in the laboratory with copper sulphate solutions, but, in the field these compounds were not so effective.

Fig. 4.—Relative effect of sulphur and copper dusts on the degree of infection caused by aeciospores of *P. graminis tritici* on leaves of Marquis wheat. Left: leaves dusted with Kolodust immediately after inoculation. Centre: dusted with copper sulphate-lime dust. Right: control, leaves not dusted.

Fig. 5.—Relative effect of sulphur and copper dusts on the degree of infection caused by *P. graminis tritici*. Leaves of Marquis wheat inoculated with urediniospores and dusted immediately afterward. Left: dusted with sulphur. Centre: dusted with copper sulphate-lime dust. Right: control, not dusted.

Fig. 6.—Relative effect of sulphur and copper dusts on the degree of infection caused by *P. triticina*. Leaves of Marquis wheat inoculated with urediniospores and dusted immediately afterward. Left: dusted with sulphur. Centre: dusted with copper sulphate-lime dust. Right: control, not dusted.

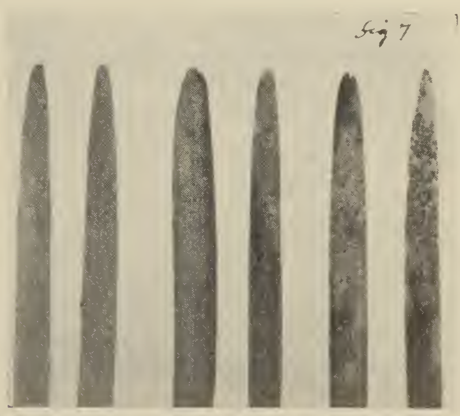

Fig. 7.—Relative effect of sulphur and copper dusts on the degree of infection caused by *P. anomala*. Leaves of Odessa barley inoculated with urediniospores and dusted immediately afterward. Left: dusted with sulphur. Centre: dusted with copper sulphate-lime dust. Right: control, not dusted.

Fungicidal Effectiveness of Various Sulphur Dusts

The ever-increasing number of proprietary sulphur compounds now being placed on the market makes field testing to determine their fungicidal value all but prohibitive in respect to time and labour. It seemed advisable, therefore, to determine the relative value of various sulphur dusts by greenhouse tests so that the most effective and the least expensive compounds could be used for tests in the field.

Greenhouse dusting tests were made with *P. graminis tritici* and *P. graminis avenae.* Ten commercial sulphur dusts were studied. These materials were obtained from several sources in the United States and Canada and were representative of the sulphur dusts used for the control of plant diseases. Tests with each of the ten dusts and an adequate check series were run at four different times.

TABLE 11.—Relative fungicidal effectiveness of various commercial sulphur dusts. Dusting tests with *Puccinia graminis.* (Average of four tests).

Fungicides	*Puccinia graminis tritici*			*Puccinia graminis avenae*		
	Percent infection	Degree of infection	Toxicity to plants	Per cent infection	Degree of infection	Toxicity to plants
Kolodust	0·6	(−)	0	0·0	0	0
Koppers dust	0·3	(−)	trace	0·0	0	slight
Gas dust	0·3	(−)	0	0·0	0	0
Electric sulphur	0·0	0	0	0·0	0	0
Canada dust	0·0	0	severe	0·0	0	severe
Swan sulphur	0·0	0	0	0·4	(−)	0
Anchor sulphur	2·1	(−)	0	2·4	(−)	0
Owl sulphur	4·5	±	trace	3·4	±	slight
Oxidized sulphur (A)	4·7	±	0	2·8	(−)	0
Oxidized sulphur (B)	6·9	±	0	3·7	(−)	0
Check (no dust)	93·0	++	0	96·0	++	0

The results given in table 11 show that all of the compounds gave a very high degree of stem rust control. Under the conditions of the experiment, some of the dusts were toxic to young plants of wheat and oats. Those plants treated with " Canada Dust " were severely etiolated. Since there is the risk that the presence of very small amounts of toxic substances may cause foliage injury, it is important to guard against impurities in sulphur fungicides.

It will be noticed that all finely-divided forms of sulphur are good fungicides. The possible difference between the various dusts is only of theoretical interest, for the mixtures were all very effective when applied immediately after the plants were inoculatd. The results show also that the coarser dusts reduced the amount of rust infection to a marked degree. As it is of considerable economic importance in the practical control of rust to use the most effective and least expensive fungicides, the results suggested the use of field experiments to compare the fungicidal effectiveness of the coarser grades of sulphur dust.

The results presented in table 12 agree very closely with the laboratory tests in which the same group of fungicides was used (Table 4). The fungicidal effectiveness increased to a marked degree as the particles decreased in size. It would seem, therefore, that particle size must be considered in the evaluation of sulphur dusts as fungicides. The covering power, adherence, and toxicity of sulphur increased progressively with the degree of fineness of the particles. In a recent paper Streeter and Rankin (91) emphasize the necessity of establishing accurate standards for determining the fineness of sulphur for dusting purposes.

TABLE 12.—Relative fungicidal effectiveness of various grades of sulphur dust. Dusting tests with *Puccinia graminis tritici* and *Puccinia graminis avenae.* (Average results of four tests).

Fungicide	*P. graminis tritici*		*P. graminis avenae*	
	Per cent infection	Degree of infection	Per cent infection	Degree of infection
Kolodust	2·6	(−)	10·4	(−)
Sulphur (300-mesh)	10·7	±	21·1	±
Sulfodust	15·1	(−)	27·1	±
Flowers of Sulphur	15·5	+	28·3	+
Sulphur (200-mesh)	15·2	+	31·6	+
Check (no dust)	99·2	++	98·0	++

Dusting tests were made also for the control of several leaf rusts of cereals. Satisfactory control of crown rust of oats (*P. coronata*), leaf rust of wheat (*P. triticina*), and the dwarf leaf rust of barley (*P. anomala*) was affected with finely-divided sulphur dusts. The results presented in table 13 show that 300-mesh sulphur was less effective than Kolodust. Grade A sulphur, a proprietary oxidized sulphur dust, proved to be less efficient than ordinary 300-mesh sulphur; while the addition of 5 per cent potassium permanganate slightly increased the effectiveness of Kolodust. The results obtained with oxidized sulphur indicated that further experiments to determine the value of other concentrations of potassium permanganate were necessary.

TABLE 13.—Relative fungicidal effectiveness of various sulphur dusts. Dusting tests with *Puccinia anomala*, *Puccinia coronata*, and *Puccinia triticina*. (Average of four tests).

Fungicide	*P. anomala*		*P. coronata*		*P. triticina*	
	Per cent infection	Degree of infection	Per cent infection	Degree of infection	Per cent infection	Degree of infection
Kolodust	10·7	(−)	5·4	±	1·1	(−)
Kolodust (plus 5% $KMnO_4$)	5·4	(−)	3·8	(−)	1·0	(−)
Sulphur (300-mesh)	5·9	+	6·8	±	1·4	±
Sulphur (oxidized)	29·4	±	11·6	±	3·6	±
Check (no dust)	100·0	++	100·0	++	66·3	++

Fungicidal Effectiveness of Oxidized Sulphur Dusts

The success obtained by Lee and Martin (55) with oxidized sulphur dusts suggested dusting tests to determine the value of such dusts for the control of cereal rusts. Tests on the stem rust fungus were used to determine if the addition of oxidizing agents to sulphur would increase its fungicidal action. Potassium permanganate ($KMnO_4$) of 300-mesh fineness, was mixed in various concentrations with sulphur dust. Several experiments were made in which the effect of various oxidized dusts were studied

Experiment I.—Kolodust containing 1, 5, and 10 per cent of potassium permanganate, and similar permanganate concentrations in ordinary 300-mesh sulphur, were prepared and subjected to greenhouse tests. The results are presented in table 14.

TABLE 14.—Fungicidal effectiveness of sulphur with different concentrations of potassium permanganate. Dusting tests with *Puccinia graminis.* (Average results of five tests).

Fungicides	Conc. of $KMnO_4$ per cent	*P. graminis tritici*		*P. graminis avenae*	
		Percentage of plants infected	Degree of infection	Percentage of plants infected	Degree of infection
Sulphur	0	10·3	±	32·8	±
Sulphur	1	6·0	±	24·5	±
Sulphur	5	3·5	(−)	7·0	(−)
Sulphur	10	3·7	(−)	10·4	(−)
Kolodust	0	7·4	(−)	18·9	±
Kolodust	1	3·3	(−)	9·8	±
Kolodust	5	0·3	(−)	7·6	(−)
Kolodust	10	1·1	(−)	7·5	(−)
Check	−	97·2	++	100·0	++

Under greenhouse conditions the addition of an oxidizing agent to dusting sulphur increased its fungicidal action. These findings agree very closely with the laboratory tests (Table 5). With both dusts, Kolodust and Sulphur (300-mesh), the percentage of plants infected with stem rust decreased with an increase, up to 5 per cent, in the concentration of potassium permanganate, A concentration of 10 per cent permanganate in sulphur gave no better results than the 5 per cent concentration. In none of the treatments was there any injury to the foliage or the plants as a whole.

Experiment II.—The results of the previous experiments suggested that it might be possible to secure, somewhere between 1 and 5 per cent, a concentration of potassium permanganate in sulphur which would be as effective as the 5 per cent mixture. An experiment was designed to ascertain the effect on stem rust infection of 1, 2, 3, 4 and 5 per cent concentrations of permanganate in Kolodust.

TABLE 15.—Fungicidal effectiveness of sulphur with various concentrations of potassium permanganate. Dusting tests with *Puccinia graminis.*

Fungicide	Concentration of potassium permanganate in per cent	Percentage of plants infected									
		P. graminis tritici					*P. graminis avenae*				
		Test 1	Test 2	Test 3	Test 4	Average	Text 1	Test 2	Test 3	Test 4	Average
Kolodust	0	3·6	1·3	1·4	0	1·6	2·0	1·7	1·0	1·2	1·5
"	1	2·3	0·0	0·0	0	0·6	0·8	1·7	0	1·4	1·0
"	2	1·1	0·0	0·0	0	0·3	0·0	0·0	0	0·0	0·0
"	3	0·0	1·4	1·1	0	0·6	0·8	1·5	0	0·0	0·6
"	4	1·3	1·3	0·0	0	0·6	3·6	0·0	0	1·6	1·3
"	5	1·1	0·0	0·0	0	0·3	0·0	1·3	0	0·0	0·3
Check	−	100·0	100·0	97·3	80·8	94·5	100·0	95·2	97·0	98·7	97·7

The results in table 15 show that ordinary Kolodust controlled rust satisfactorily. The addition of 1 per cent potassium permanganate increased slightly its fungicidal action. Increasing the concentrations of permanganate to 2 per cent gave a further increase, but permanganate concentrations of 3, 4 and 5 per cent gave no better results than the 2 per cent mixture. Although the differences observed in this experiment are very small, the results indicate the possibility of increasing the fungicidal value of sulphur by the use of oxidizing agents.

These greenhouse results conform with the field results of Lee and Martin (56) who found that against a sugar cane disease, called "eye-spot", oxidized sulphur dusts were more effective than ordinary dusting sulphurs. However, field dusting carried out on a large scale under natural rust epidemic conditions must serve as the final test in the evaluation of oxidized sulphur dusts for the the control of cereal rusts.

Experiment III.—The purpose of this experiment was to determine whether or not potassium permanganate alone had any toxic effect on rust fungi. Potassium permanganate was mixed with Kolodust, a sulphur carrier, and Talc ($H_2Mg_3S_4O_{12}$), an inert dust, as a non-sulphur carrier. These compounds were compared with ordinary Talc and Kolodust. Five tests were made at different times.

TABLE 16.—Fungicidal effectiveness of potassium permanganate in sulphur and talc carriers. Dusting tests with *Puccinia graminis tritici* and *Puccinia graminis avenae.*

Fungicide	Percentage of plants infected											
	P. graminis tritici						*P. graminis avenae*					
	Test 1	Test 2	Test 3	Test 4	Test 5	Average	Test 1	Test 2	Test 3	Test 4	Test 5	Average
Talc	97·2	56·0	90·0	91·2	83·3	83·5	94·8	100·0	95·2	95·8	100·0	97·2
Talc+5% $KMnO_4$	60·0	41·8	78·0	70·2	78·2	65·6	82·0	92·1	92·8	93·4	73·5	87·1
Kolodust	1·8	1·1	6·0	3·4	1·2	2·7	15·7	9·1	7·1	10·8	7·3	10·0
Kolodust+ 5% $KMnO_4$	1·0	0·0	0·9	1·1	0·0	0·6	11·6	8·0	5·0	7·4	3·4	7·1
Check (no dust)	94·8	100·0	97·0	98·0	100·0	97·9	98·0	100·0	100·0	99·0	100·0	99·4

As is shown in table 16, Talc alone did not prove very efficacious, although it reduced slightly the amount of stem rust infection. Talc plus 5 per cent potassium permanganate gave better control. From these results it is evident that potassium permanganate is slightly toxic to the urediniospores of cereal rust fungi. The effectiveness of Kolodust plus 5 per cent potassium permanganate suggested further experiments to determine if the increased fungicidal effect might be attributed to the toxic action of the potassium permanganate rather than to its oxidizing effect on sulphur.

Factors Influencing the Fungicidal Effectiveness of Sulphur Dusts

Temperature.—In his experiments on the control of snapdragon rust with sulphur, Butler (15) found that sulphur was quite ineffective at low temperatures. Toxicity tests at different temperatures with spores of *Botrytis cinerea* Pers. were made by Tisdale (95) and his results indicate that colloidal sulphur is most toxic at high temperatures. Goldsworthy and Smith (30) claim that sulphur acts best at high temperatures and suggest that the lack of success experienced by many growers in controlling rust of peaches may be attributed to the fact that the temperature was not high enough at the time of application. Clark (16) and Doran (21) concluded that a fungus presents its greatest resistance to the action of fungicides when the temperature is at the optimum for spore germination. To study the influence of temperature on the fungicidal efficiency of sulphur in the control of cereal rusts, a series of dusting tests were made under controlled conditions in the greenhouse.

Wheat plants were grown in 5-inch pots. One set of plants was grown at a temperature range of from 10° to 12° C., another, of from 22° to 24° C. Soil

temperature tanks, so adjusted that they could be used as moist incubation chambers, were maintained at the two temperature ranges. The plants were inoculated in the usual way with urediniospores of *P. graminis* and then dusted with sulphur. Immediately following inoculation and dust application, one set of plants was placed in moist chambers maintained at from 10° to 12° C., and another set of plants, in moist chambers maintained at from 22° to 24° C. After 48 hours, both sets were taken from the chambers and placed in two different greenhouses in which the respective ranges of temperature mentioned above were maintained during the entire period of the experiment. Two tests were included in each experiment, one in which the plants were dusted with sulphur just before inoculation, and another immediately afterward. The complete experiment was run at two different times.

The results of these experiments are summarized in table 17 and show that the fungicidal value of sulphur is not significantly influenced by temperature. In all the tests rust development was retarded at the low temperature. It will be noticed that a slight amount of infection occurred at from 10° to 22° C. when the plants were dusted immediately after inoculation. In this instance uredinia appeared only at the tips of the leaves. This can be explained by the fact that large guttation drops form on the tips of leaves when plants are held at low temperatures in moist chambers. The presence of moisture at the tips of the leaves would reduce the toxic effect of the sulphur and produce conditions favourable for spore germination and growth of the germ tubes. It would seem that a temperature as low as 10° or 12° C., has very slight, if any, influence on the toxicity of sulphur in controlling stem rust of wheat.

In table 18 are summarized the results of another experiment to determine the influence of temperature on the fungicidal efficiency of sulphur when it was applied to the plants at various intervals after inoculation. Although stem rust developed more slowly at 10° to 12° C. than at 20° to 24° C., sulphur, when applied within a period of four hours after inoculation, prevented any significant amount of rust infection at the lower temperature, while at the higher temperature it was equally effective for only two hours.

TABLE 17.—Influence of temperature on the fungicidal effectiveness of sulphur dust. Dusting tests with *Puccinia graminis tritici*. (Average of two tests).

Temperature (C.)	Time of sulphur application	Length of incubation period in days	Percentage of plants infected	Degree of infection
10°-12°	Before inoculation	12	0	0
	After "	12	3·8	(−)
	Check (no dust)	12	80·0	+
22°-24°	Before inoculation	6	0	0
	After "	6	0	0
	Check (no dust)	6	91	++

In each case the efficiency of the fungicide diminished in direct relation to the length of time elapsing between inoculation and dust application. At from 10° to 12° C. the percentage of plants which became infected at the various intervals was considerably lower than the percentage infected at the corresponding intervals at the higher temperature. This condition can be accounted for by the slower growth of the germ tubes at the lower temperature rather than by an increased activity of the sulphur at the higher temperature. Temperature does not seem to be a critical factor in determining the fungicidal efficiency of

sulphur in controlling rust. The results, however, do emphasize the importance of applying the sulphur before the rust pathogen has entered its host, and indicate that the toxic action of sulphur is exerted on the pathogen while it is merely in physical association with the host.

TABLE 18.—Influence of temperature on the fungicidal effectiveness of sulphur when various intervals elapsed between inoculation and dust application. Dusting tests with *Puccinia graminis tritici*. (Average of four tests).

Interval between inoculation and dust application hours	10°–12° C.		22°–24° C.	
	Percentage of plants infected	Degree of infection	Percentage of plants infected	Degree of infection
0	0	0	0	0
1	0	0	0	0
2	0	0	4	(−)
3	0	(−)	9	(−)
4	4·4	(−)	4·5	(−)
5	9	(−)	4·5	(−)
6	10	(−)	28	±
7	7	±	40	±
8	9	±	31	±
9	23	±	48	±
10	17	±	73	±
11	30	±	83	+
12	47	±	92	++
Check (no dust)	93	+	100	++

Free moisture.—Experiments were made to determine the influence of free moisture on the efficiency of sulphur at the time of, and subsequent to, inoculation with rust.

A number of pots containing seedlings of Marquis wheat were divided into two series. The plants in one series, hereafter called the "wet" series, were sprinkled with water each day during the experiment. The amount of water applied was about equivalent to a heavy dew. The plants in the other series, the "dry" series, were left unsprinkled during the experiment. Each series was again divided into three sets. One set was dusted with Kolodust, another with Sulfodust, and a third was left undusted, as a check.

Immediately after the dust had been applied, and thereafter, at one day intervals, up to the twelfth day, fifty plants of each set were inoculated with urediniospores of stem rust. Plants in the wet series were inoculated by spraying a spore suspension onto the plants, while inoculations in the dry series were made by applying dry spores to the unmoistened leaves. After inoculation all the plants were placed in moist chambers at a temperature range of from 20°-22° C. The plants of the wet series remained in the moist chamber for 48 hours. The length of the inoculation period for the dry plant series was 24 hours. After incubation the plants were taken from the chambers and placed on benches in the greenhouse. With the exception of the daily sprinkling of the wet series, both series of plants were held under identical greenhouse conditions for the duration of the experiment. Final data on the percentage of plants infected were recorded 14 days after inoculation. The experiment was run at two different times.

Under the conditions of the experiment spore germination, as well as the efficiency of the fungicide, would be influenced by the amount of moisture present at the time of inoculation and subsequently; hence, the infection results are only indicative of the actual effect of free moisture on the fungicidal efficiency of sulphur. As may be observed from table 19, the fungicidal value of sulphur seemed to be markedly reduced when free moisture was abundant at the time of, and subsequent to, inoculation. Under wet conditions considerable rust

infection occurred when only one day had elapsed between dust application and time of inoculation; whereas both sulphur dusts were effective for long periods under relatively dry conditions. When the plants were dry a very small number of them became infected, even when they were not inoculated until twelve days after the dust was applied. In these tests Kolodust was slightly more effective than Sulfodust. From the data it would appear that the fungicidal efficiency of sulphur is influenced by the presence of free moisture at the time of, and subsequent to, the application of the sulphur.

TABLE 19.—Influence of free moisture at the time of and subsequent to dusting on the fungicidal effectiveness of sulphur. Dusting tests with *Puccinia graminis tritici*.

Interval between dust application and inoculation days	Percentage of plants infected					
	Kolodust		Sulfodust		Check (no dust)	
	Wet	Dry	Wet	Dry	Wet	Dry
0	1	0	1	0	99	58
½	8	0	18	0	98	57
1	29	1	43	3	94	68
2	41	0	44	3	97	75
3	52	0	54	3	100	75
4	93	0	92	5	100	76
5	80	5	74	3	94	74
6	81	0	91	2	91	69
7	51	4	65	3	82	55
8	91	0	85	7	96	75
9	48	0	80	0	97	70
10	73	4	91	5	93	67
11	63	5	82	7	88	65
12	93	2	97	5	96	77

A study was made also of the adherence of sulphur dusts to the leaves of cereal plants. In these experiments dusted Marquis wheat plants were exposed for various periods to a shower of water and then inoculated with stem rust. This shower would correspond in intensity to an ordinary rain to which plants would be subject under field conditions. As may be observed from the data in table 20, a large number of dusted plants became infected when they were exposed to the shower for periods longer than 10 minutes.

TABLE 20.—The effect of exposing dusted plants to a shower of water for different periods before inoculation on the fungicidal effectiveness of sulphur dusts. Dusting tests with *Puccinia graminis tritici* (Average of two tests).

Time dusted plants were exposed to shower of water minutes	Percentage of plants infected		
	Kolodust	Sulfodust	Check (no dust)
0	0	1·3	97·4
1½	0	1·3	98·2
3	10·3	31·2	97·4
5	22·0	25·9	97·6
10	23·4	39·0	95·5
15	70·9	69·4	95·0
30	68·2	67·2	96·7
45	79·6	93·8	100·0
60	82·3	96·9	100·0
120	79·3	93·4	100·0

When plants were exposed for 15 minutes and then inoculated with stem rust, the protective value of sulphur was practically lost. The fungicidal value

of the sulphur dusts diminished in direct proportion to the time the plants were subjected to the shower. Kolodust, owing probably to the fineness of its particles and its greater ability to adhere to the foliage, afforded the plants greater protection than did the Sulfodust. The results emphasize the importance of particle size in the adherence of sulphur dusts, and suggest that meteorological factors may play a very important part in the control of cereal rusts by dusting.

Physical conditions.—In the foregoing experiments it appeared that the size of the particles was correlated with the fungicidal value of sulphur. If an oxidation product of sulphur is the toxic principle, it might be expected that the more rapid oxidation of the smaller particles into toxic substances would partially account for the greater efficiency of the finer dusts. It was observed, too, that the finer dusts absorb more moisture than the coarser ones. If this absorption was sufficiently pronounced, it might easily inhibit germination by reducing the available moisture below the amount required for the germination of the spores.

In order to ascertain whether physical properties of the dust influence the effectiveness of sulphur, and to determine if dusts on the surface of the plants offer any mechanical obstruction to the penetration of the germ tubes, thereby decreasing the amount of infection, a number of inert dusts of approximately the same degree of fineness were used in comparison with two sulphur dusts in some greenhouse tests. Chalk, China clay, and Talc, three finely-divided inert dusts with marked water absorbing capacity, were tested against Kolodust and Sulfodust.

An examination of table 21 shows that the inert dusts were not effective in reducing the amount of leaf and stem rust infection, whereas the sulphur dusts reduced infection to a marked degree. These results agree closely with those of the laboratory tests in which it was shown that the same inert dusts were not toxic to the growth of urediniospores of rust fungi (Table 6).

TABLE 21.—Relative fungicidal effectiveness of various inert and sulphur dusts. Dusting tests with *Puccinia graminis tritici*, *Puccinia graminis avenae*, and *Puccinia triticina*.

Dust	Percentage of plants infected					
	Dusted before inoculation			Dusted after inoculation		
	P. gr. tritici	*P. gr. avenae*	*Puccinia triticina*	*P. gr. tritici*	*P. gr. avenae*	*Puccinia triticina*
Kolodust	1	2	0	4	24	15
Sulfodust	1	4	1	9	29	22
Chalk	98	100	97	99	100	99
Talc	98	98	100	96	100	98
China Clay	98	99	99	96	100	100
Check (no dust)	97	100	100	99	100	100

Interval between inoculation and dust application.—In dusting practice it is recognized that timeliness of application is an important factor in determining the effectiveness of any treatment It has been shown that the fungicidal efficiency of sulphur becomes progressively less the longer the time is between plant inoculation and dust application. Dusting tests were made to discover how soon after inoculation sulphur had to be applied in order to prevent the development of rust An experiment in which stem rust was used as the test object was run at two different times. The results of these experiments are summarized in table 22.

TABLE 22.—Effect of the interval between inoculation and time of application on the effectiveness of sulphur dust. (Temperature 22°–25° C.)

Interval between inoculation and dust application hours	*P. graminis tritici*		*P. graminis avenae*	
	Percentage of plants infected	Degree of infection	Percentage of plants infected	Degree of infection
0	1	(−)	0	(−)
1	3	(−)	8	(−)
3	3	(−)	16	(−)
6	14	±	25	±
12	85	+	74	+
18	89	+	86	+
24	92	+	100	++
48	97	++	99	++
Check	100	++	100	++

As may be observed from the data, the development of rust was markedly inhibited when the sulphur was applied within three hours after the plants were inoculated. Sulphur was quite ineffective after an interval of twelve hours or more. Once the fungus had become established in the host it was beyond the influence of the fungicide, and subsequent applications of sulphur were of no avail.

Effect of Sulphur on the Type of Rust Infection

The foregoing studies have shown that sulphur prevents a rust organism from establishing pathogenic relation with its host. Evidence has been adduced also to show that if sulphur is applied after infection has taken place it is ineffective in preventing this relationship from being set up. It seemed worth while to ascertain whether the application of sulphur subsequent to infection influenced the ultimate type of pustule development.

Marquis wheat plants were inoculated with *P. graminis tritici*. A pure physiologic form (Form 21) which produces a definite homogeneous infection type on Marquis wheat was used. Immediately following inoculation, and at one-day intervals up to and including the tenth day, fifty plants were heavily dusted with sulphur. An adequate number of plants were left untreated as checks. Fourteen days after inoculation the percentage of plants infected and the type of infection were recorded.

As the results in table 23 indicate, no infection occurred on plants dusted immediately after inoculation. Where the interval between inoculaton and dust application was one day or more, the ultimate type of infection and the percentage of plants infected did not vary significantly, whether this interval was 2, 4, 6, 8, or 10 days.

TABLE 23.—The effect of sulphur on the development of uredinia of *Puccinia graminis tritici*.

Interval between inoculation and dust applications in days	Percentage of plants infected	Degree of infection	Development of uredinia
0	0	0	No flecks
1	89	(−)	Retarded
2	98	±	Retarded
4	99	++	Slightly retarded
6	96	++	Normal
8	100	++	"
10	99	++	"
12	98	++	"
Control (not dusted)	100	++	"

It is possible that the presence of the toxic principle of the sulphur may retard the growth of the young infecting hyphae even for a short time after the germ tube has entered the host cell. However, once the mycelium becomes established inside of the host it is beyond the influence of the toxic principle of the fungicide and develops normally. According to Goldsworthy and Smith (30) the effect of polysulphides on the spores and germ tubes of the peach rust fungus is direct, the sulphide enters the germ tube and reduces the protoplasm, causing the death of the organism.

C. Field Experiments on the Prevention of Cereal Rusts by Sulphur Dusting

Observations on Severity of Rust Epidemics in Manitoba

Before proceeding with a discussion of each year's results it seems advisable to give a brief account of the years in which the experiments were carried out. Heavy epidemics of stem and leaf rusts of wheat developed in Manitoba in 1925. The first collection of the uredinial stage of stem rust was made on June 23 at Morden, Man. At this time a light trace of leaf rust was generally present. By July 15, scattered primary infections of stem rust were present throughout the south and central parts of the province. Rust developed very rapidly in the latter part of July, but cool weather early in August checked its development to a marked degree. Unfortunately, the cool weather also checked plant growth and gave the rust a chance to become thoroughly established. The final result of the 1925 epidemic of stem rust was an extremely patchy development of rust in which local environmental conditions played an extremely important part. Late crops were damaged considerably while the earlier maturing varieties escaped severe injury. At Winnipeg, late-sown Marquis wheat was heavily attacked by both leaf rust and stem rust.

In 1926 the uredinial stage of stem rust was not found until June 30. By July 15 leaf and stem rust could be found without much difficulty in southern Manitoba but further north and west in the province, there was practically no trace of rust. The absence of heavy infestations of rust in the spring-wheat area of the United States probably accounted, in part, for the mild epidemic of this disease in Western Canada. Just how important each environmental factor was was difficult to determine, the resultant effect, however, was that Manitoba had an almost rust free year.

The year 1927 will be remembered as a bad rust year. Rust developed in severe epidemic form in most parts of Western Canada. On account of the excessive precipitation during the month of May, seeding was retarded from 10 days to four weeks. It therefore happened that even in the same districts there was little uniformity in the maturing of the grain.

The first trace of rust was discovered in experimental field plots at Morden and Winnipeg on July 6. By July 18 a light infection of both leaf and stem rust was general in Manitoba. Several hot days in late July stimulated the development of rust in the plants and resulted in a sudden increase in the amount of inoculum. The first week of August was cool, and both wheat and rust made slow progress during that time, although heavy dews favoured rust infection. High daily temperatures prevailed early in August and stimulated rapid development of the mycelia in the plants, so that by August 15 the situation became exceedingly dangerous. Following that date the progress of the rust proceeded apace, with the result that Western Canada suffered one of the worst epidemics in history.

In 1928 the amount of initial rust inoculum, as indicated by spore traps, was smaller than in 1925, 1926, or 1927. Conditions were not unfavourable for the development of rust, and still a general destructive outbreak did not occur. Generally, stem rust developed slowly in 1928, and before it had time to multiply

and spread sufficiently to cause severe damage, the crop had ripened and thus escaped appreciable loss. In a few localities, however, wheat fields were heavily rusted. Leaf rust was present as usual, but it appeared somewhat later than in the preceding years and was much less severe.

Rust made little progress in 1929. The first traces of leaf rust and stem rust of wheat were found at Brandon and Portage, Man., on July 3. By July 5 scattered primary infections were present in southern Manitoba. Throughout the month of July the amount of rust gradually increased. The weather was extremely hot and dry, but heavy dews occurred during this period and thus permitted fresh infections to take place. The wheat ripened early and uniformly, and by the end of July many fields were beyond the stage where rust could do them any appreciable damage. Oats, in general, bore a fairly heavy infection of stem rust but were not very seriously damaged.

In 1930 stem rust of wheat was first observed on June 26 at Morden, Man. Weather conditions during late June and early July were very favourable for its development. Frequent rains and high temperatures favoured rapid rust development. By July 20, stem rust of wheat had become quite prevalent and a severe epidemic appeared imminent. From July 20 to the end of the growing season, the country suffered an unusual drought and high temperatures hastened the early ripening of the wheat. These conditions apparently checked further progress of this rust, so that the damage caused by it was not excessive. Stem rust of oats, however, was fairly prevalent in some districts of Manitoba, and the crop in these districts suffered considerable damage. Crown rust of oats and leaf rust of wheat, although present, were not nearly so abundant as stem rust.

PRELIMINARY FIELD DUSTING TESTS

Preliminary field tests to determine the effect of sulphur on the control of cereal rusts were made in 1925. Sulphur was applied to small plots of Marquis wheat at frequent intervals from July 2 to August 25. In that year, a severe rust year, dusting with sulphur prevented the development of leaf rust and stem rust to a striking degree, and consequently increased yield and improved the quality of grain. The preventable loss due to rust, as shown by the increased yield, was 37.4 bushels per acre, while the grade of the grain was raised from "Feed Wheat" to No. 1 Northern. In that year, the difference in marketable value of these two grades was 50 cents per bushel. Dusting with sulphur appeared therefore an effective means of preventing rust, and seemed worthy of a much more thorough investigation.

TABLE 24.—Results of dusting Marquis wheat with sulphur in 1–40th-acre plots at Winnipeg, in 1925. Effect of dusting at the rate of 15 pounds per acre per application, on the amount of rust infection, and on the consequent yield and quality of grain. (Dusting period = July 2 to August 31, 1925).

Interval between dust applications days	Total number dustings	Per cent leaf rust severity	Per cent stem rust severity	Yield per acre bushels	Weight per bushel pounds	Grade	Yield increase per acre over check bushels
Check	0	70	85	17·7	49	Feed	–
14	4	75	75	24·5	48	Feed	6·8
7	8	65	60	35·1	56	3°	17·4
4 to 3	17	45	50	43·1	60	2°	25·4
3 to 2	24	15	5	55·1	63	1°	37·4

Table 24 gives the dusting schedule followed at Winnipeg in 1925, together with the results showing the effect of dusting on the amount of rust at harvest time, and on the consequent yield and grade of Marquis wheat. The range

of rust infection in dusted and undusted plots is shown in figures 8 and 9, and the effect of dusting on the size and plumpness of heads and kernels is illustrated in figures 10 and 11.

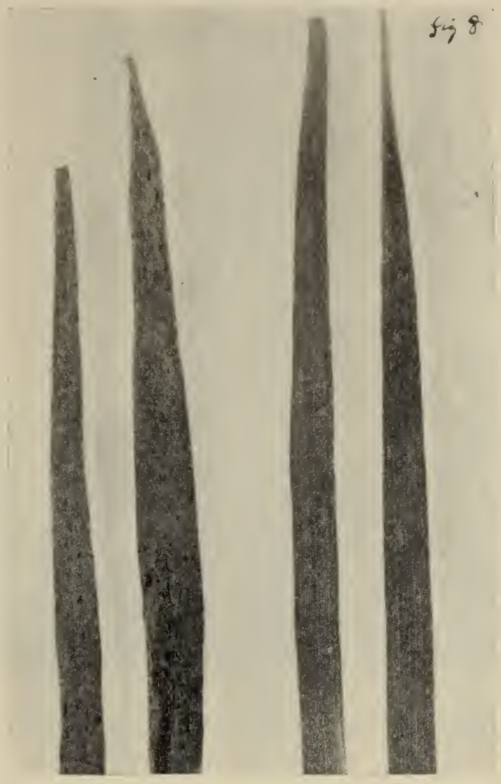

FIG. 8.—Leaves of Marquis wheat grown in plots at Winnipeg in 1925, showing the effect of controlling leaf rust with sulphur dust. Left: rusted leaves, not dusted. Right: dusted leaves, not rusted.

FIG. 9.—Stems of Marquis wheat grown in plots at Winnipeg in 1925, showing the range of stem rust infection in sulphur dusted plots. Left to right—Dusted stems (no rust), trace, 20 per cent, 50 per cent, Check (no dust) 80 per cent.

Fig. 10.—Heads of Marquis wheat grown in plots at Winnipeg in 1925. Left: heads of rusted undusted plants. Right: heads of non-rusted dusted plants.

Fig. 11.—Effect of controlling rust is illustrated by the size and plumpness of kernels of Marquis wheat grown in plots at Winnipeg in 1925. Left: kernels of dusted wheat, not rusted. (Weight per bushel 63 pounds). Right: kernels of rusted wheat, undusted. (Weight per bushel 49 pounds).

From an economic and practical viewpoint, two important problems presented themselves, the solution of which awaited further experiments. Would dusting with sulphur be a profitable method of controlling rust? Could large fields of grain be quickly and thoroughly treated with dust fungicides? In an attempt to answer these questions and to obtain additional and definite information concerning the value of dusting, extensive systematic field experiments were designed (1) to determine the effect of various weather conditions on this method of control, the length of dusting period, the rate and frequency of dust application; (2) to study the relative value of various dust fungicides; and (3) to arrive at a solution of some of the practical difficulties of dusting large fields of small grain crops. In other words, it was hoped that the investigation would yield information which would make it possible to arrive at an effective, practical, and profitable program of sulphur applications for rust control.

Preliminary field tests carried out in 1925 demonstrated the effectiveness of sulphur in preventing rust infection even under conditions of a natural epidemic. Once the effectiveness of sulphur dusting was proved, its feasibility as a practical method of preventing rust seemed to depend on whether or not comparable results could be obtained by the same procedure in different years. During the following years, up to 1930, a comprehensive series of small plot experiments were carried on. In addition to the small plot experiments at Winnipeg in 1926, field tests with horse-drawn dusters were commenced on ordinary farms in Manitoba. In 1927 the small plot studies were repeated and extended, and much more extensive dusting tests in the field were undertaken both with ground and with aeroplane dusters. The results of these field experiments have been reported by Bailey and Greaney (2, 3, 4). After 1927 the field experiments were continued. Extensive field tests were made in 1928, 1929, and 1930.

It seems worthwhile to bring together the results of the field experiments for the full six years, as by doing so a better basis for the evaluation of sulphur dusting as a prevention of cereal rusts is provided. The results of the field dusting experiments are summarized in tables 25-50 inclusive. A detailed analysis of these results appears under the captions: " Small Plot Experiments " and " Field Trials."

Small Plot Experiments

The larger part of the small plot experiments was concerned with the prevention of leaf rust and stem rust of wheat. Experiments to determine the value of dusting with sulphur for the control of crown rust and stem rust of oats, and some of the minor diseases of wheat were made in 1928, 1929, 1930, and 1931. Data accruing from the small plot experiments were used to obtain definite information concerning the relation between the amount of rust infection and the yield of wheat and oats.

MATERIALS AND METHODS

Each year of the investigation a small field which had been summer-fallowed the previous season was chosen for the experiments. For the purpose of the small plot studies the field was sown late to blocks of Marquis wheat and Victory oats. This belated sowing on summer-fallow afforded rank succulent stands of grain which usually became heavily infested with rust. The grain was planted with an ordinary seeder, the drills being six inches apart. About a month after planting the field was divided into plots. These varied in size in different years from 1/40th-acre in 1925 to 1/400th-acre in 1930. They were rectangular in shape and particularly suitable for hand-dusting and harvesting operations. Buffer strips were left between the plots to serve as protection against dust drift. The arrangement of plots, as shown in figure 12, extended over a number of series in each experimental block.

In 1925, 1926, 1927, and 1928 the field tests were made under conditions of natural epidemics of rust. The results obtained during these four years indicated that every season furnished a new combination of environmental conditions, which, in turn, influenced greatly the expression of rust in the maturing crop and the effectiveness of the dust treatment. In 1929 and 1930, in order to insure a sufficient amount of rust infection, the grain was grown under conditions of artificially induced rust epidemics in conjunction with naturally occurring ones.

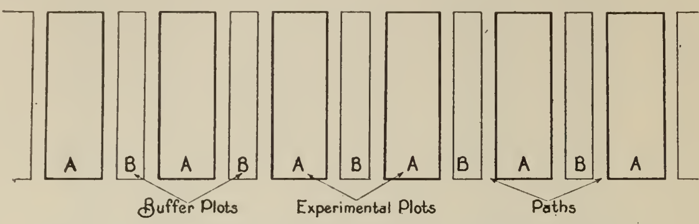

FIG. 12.—Arrangement of plots in sulphur dusting experiments.

Dusting operations were commenced each year just as soon as rust appeared in the district, but not necessarily in the plots. Thereafter, sulphur was applied at regular, or at special, intervals until the crop was beginning to ripen. Except where otherwise mentioned, Kolodust (Niagara colloidal sulphur dust) was used throughout the tests. The dust was applied at a given rate by means of small hand-dusters (Fig. 13). In this paper the amount of dust used at each application is expressed as rate in pounds per acre.

FIG. 13.—Dusting plots of wheat with sulphur to control rust.

Final leaf rust readings, based on the scale of stem rust percentages adopted by the Office of Cereal Crops and Diseases, United States Department of Agriculture, were made when the leaves were still green; those for stem rust, just before the plants ripened. Rust estimates were made by Dr. T. Johnson and Mr. B. Peturson of the Dominion Rust Research Laboratory, who did not know what treatment any plot had received.

In 1925, 1926, and 1927 single plots were used for each dust treatment, while a number of untreated check plots were arranged at random in each experimental block. At harvest time a number of rod rows were removed from each plot. The

yield results were then obtained by harvesting and threshing each rod row separately. The average of these rod rows was used to compute the yield of each plot in bushels per acre.

In 1928 replication was used as a means of diminishing error due to soil heterogeneity, and errors due to measurement. Each treatment was replicated three times, so that four systematically distributed plots were used for each treatment. The average yield of the four plots was used to compute the yield in bushels per acre.

The experiments in 1929 and 1930 were planned with consideration of the relation which must exist between the arrangement of the experiments and the statistical analysis of the data. In these years Latin Square and Randomized Block experiments were used, and the analysis of variance method devised by Fisher (26) was employed in analyzing the yield data. A complete discussion of the methods and advantages of arranging plots in a Latin Square and of the analysis of variance is given by Fisher (26). Fisher and Wishart (27) give simple and direct methods for the analysis of data of Latin Square and Randomized Block experiments. A review of modern methods of field experimentation in which particular attention has been given to methods of calculation has been published by Goulden (37). The statistical methods used in the present study are adapted from these papers.

In 1928, 1929, and 1930 the yield results were secured by harvesting and threshing each plot separately. In order to minimize errors due to border effect the outside drill rows and six inches from the end of each plot were removed by hand before harvest.

Each year during the course of the investigation weight per bushel was ascertained by bulking the threshed grain of each replicated series and weighing according to Canadian Grain Standards. The correct marketable grade for each treatment was determined by officials of the Western Grain Inspection Division, Winnipeg, Man.

In the analysis of the results for the four years, 1925 to 1928, the average yield figures for the various dust treatments were compared. The yield data were not analyzed statistically. The Latin Square and Randomized Block experiments of 1929 and 1930 were subjected to statistical enquiry. The analysis of variance method was used in analyzing the yield data and the significance of the results obtained was determined by reference to tables by Fisher (26).

In order to demonstrate the arrangement of Latin Square experiments and the analysis of variance, the results of an experiment which was made in 1930 to determine the effect of rate and frequency of dust application on rust control will be used (table 28).

In the analysis of variance section of table 28 estimates of variance are given for rows, columns, treatments, and error. The important feature of this analysis is the comparison of the estimates of variance for treatments with that of error. If there are no treatment differences it would be expected that the variance estimated from the treatments would differ from that due to error only by an amount which could easily be obtained by chance. If the former is not significantly greater than the latter, it can be concluded, in general, that no real differences between the treatments exist or that the experiment has not been sufficiently accurate to bring out these differences. In table 28, the estimate of variance for treatments is significantly greater than that due to error. Hence, it may be assumed that some real differences exist between the various treatments in this experiment.

The actual comparison of estimates of variance is made by the application of Fisher's Z test. The test consists in finding the difference between one half the natural logarithms of the variance for treatments and the variance for error, and determining the significance of this difference by reference to tables provided by Fisher (26). In the present study the 5 per cent point (20:1 odds) is taken as the minimum level of significance. In table 28 the observed value of

Z exceeds the 5 per cent point and hence the conclusion is drawn that the differences observed in this experiment are undoubtedly significant.

From the analysis of variance table the standard error of the experiment is calculated directly. Thus, in this test, the standard error of a single plot is the square root of the error estimate of variance.

$$\text{Standard Error} = \frac{621 \cdot 01}{110} = \sqrt{5 \cdot 64} = 2 \cdot 37$$

This may be expressed as the standard error of means of treatments.

$$\text{Standard Error of Mean} = \sqrt{\frac{5 \cdot 64}{\sqrt{12}}} = \frac{2 \cdot 37}{3 \cdot 46} = 0 \cdot 68$$

The standard error of the mean yields for the respective treatments and the minimum significant yield difference between treatments are added to the summary table (Table 28). When once the effect of the treatments is shown to be definitely significant, individual differences may be examined in the light of the standard error.

In comparing yield differences between any two treatments, differences of less than three times their standard error are ascribed to chance; differences as great or greater than these are significant and ascribed to such dusting effects as the experiment was designed to examine.

THE PREVENTION OF LEAF RUST AND STEM RUST OF WHEAT

Effect of Rate of Dust Application

The rates tested were 15, 30, and 45 pounds per acre per application. These rates were chosen because of the ease with which they could be applied by hand dusting machines. The dusters were adjusted permanently to distribute dust at the rate of 15 pounds per acre. When treatments of 30 and 45 pounds per

TABLE 25.—Influence of rate of application. Effect of dusting Marquis wheat with sulphur at 7-day intervals on the amount of leaf rust and stem rust, and on the consequent yield, and quality of grain, at Winnipeg, in 1925, 1926, 1927, and 1928.

Year and duration of dusting period	Rate of dust per acre pounds	Per cent leaf rust severity	Per cent stem rust severity	Yield per acre bushels	Weight per bushel pounds	Grade	Yield increase per acre over check bushels
1925	0	70	85	17·7	49	Feed	–
July 2 — Aug. 25...............	15	65	40	35·1	56	3°	17·4
	30	60	75	24·7	51	#4	7·0
1926	0	5	10	41·1	60	1°	–
July 5 — Aug. 6..............	15	tr	tr	41·6	60	1°	0·5
	30	tr	tr	40·5	61	1°	–
	45	tr	tr	40·1	60	1°	–
1927	0	62	87	12·2	45	Feed	–
July 18 — Sept. 9...............	15	32	35	23·4	54	#5	11·2
	30	30	35	20·6	54	#5	8·4
	45	25	35	25·0	55	#5	12·8
1928	0	72	57	21·6	59	2°	–
uly 18 — Sept. 9...............	15	60	42	31·2	60	2°	9·6
	30	51	22	29·1	59	2°	7·5
	45	49	20	31·3	60	2°	9·7

acre were made, the same machines were employed, and the plots were dusted two and three times, respectively. Uniformity and reasonable accuracy were therefore maintained in the rates of application.

TABLE 26.—Influence of rate of application. Effect of dusting Marquis wheat with sulphur at 3-4 day intervals on the amount of leaf rust and stem rust, and on the consequent yield, and quality of grain, at Winnipeg, in 1925, 1927, and 1928.

Year and duration of dusting period	Rate of dust per acre pounds	Per cent leaf rust severity	Per cent stem rust severity	Yield per acre bushels	Weight per bushel pounds	Grade	Yield increase per acre over check bushels
1925	0	70	85	17·7	49	Feed	–
July 2 — Aug. 25	15	45	50	43·1	60	2°	25·4
	30	21	35	50·8	64	1°	33·1
1927	0	62	87	12·2	45	Feed	–
July 18 — Sept. 9	15	22	30	33·3	56	#4	21·1
	30	20	15	30·5	53	#5	18·3
	45	25	10	33·4	55	#5	21·2
1928	0	70	56	22·4	59	2°	–
July 17 — Aug. 29	15	50	20	25·4	59	2°	3·0
	30	51	22	31·2	59	2°	8·8
	45	35	6	35·1	60	2°	12·7

The dusting schedules followed in 1925, 1926, 1927, and 1928, together with the effect of various rates of sulphur application on the amount of leaf rust and stem rust infection, and the resulting yield and quality of the grain are summarized in tables 25 and 26. The influence of rate of application on the effectiveness of sulphur in 1929 is shown in table 27; while the 1930 data are given in table 28. The results of the experiments for the full six years are presented graphically in figures 14 and 15.

TABLE 27.—Influence of various rates and frequencies of sulphur dust application on the amount of stem rust infection, and on the consequent yield and quality of Marquis wheat in 1–400th-acre plots in a Latin Square, at Winnipeg, in 1929. (Dusting period July 9 to August 10, 1929).

Summary of Results

Treatment symbol	Total number of dustings	Per cent stem rust severity	Yield per acre bushels	Weight per bushel pounds	Increase in yield per acre over check bushels
A	2	24	25·2	63	0·7
B	3	16	27·2	64	2·7
C	5	10	28·2	64	3·7
D	9	5	27·9	64	3·4
E	17	tr	27·2	64	2·7
F	3	16	27·8	64	3·3
G	5	11	28·1	64	3·6
H	9	2	27·6	64	3·1
I	17	tr	27·4	64	2·9
J	3	18	26·6	64	2·1
K	5	5	28·0	64	3·5
L	9	tr	28·8	64	4·3
M	17	tr	28·4	64	3·9
N	0	33	24·5	63	–

KEY TO TREATMENTS

Rate of dust per acre per application	A	B	C	D	E	F	G	H	I	J	K	L	M	N
	Interval between dust applications in days													
pounds	21	14	7	4–3	3–2	14	7	4–3	3–2	14	7	4–3	3–2	Ch.
0	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	X
15	X	X	X	X	X	.....	.....	.....	.....	.....	.....	.....	.....	.....
30	.....	.....	.....	.....	.....	X	X	X	X	.....	.....	.....	.....	.....
45	.....	.....	.....	.....	.....	.....	.....	.....	.....	X	X	X	X	.....

YIELD ANALYSIS OF VARIANCE

Source of variance	Sums of squares	Degrees of freedom	Variance of mean square
Rows	353·13	13	27·16
Columns	3,485·07	13	268·08
Between treatments	49·04	3	16·35
Within treatments	139·98	10	14·00
Error	2,979·82	156	19·10
Total	7,007·04	195	

Results not significant

TABLE 28.—Influence of various rates and frequencies of sulphur dust application on the amount of stem rust infection, and on the consequent yield and quality of grain.

Wheat (Marquis), Winnipeg, 1930

I	I	J	K	F	H	C	B	G	E	A	L	D
II	C	E	A	L	K	G	I	F	B	D	H	J
III	A	I	G	B	F	J	D	L	C	H	E	K
IV	H	B	L	C	D	F	J	A	G	E	K	I
V	D	C	J	I	A	E	G	H	L	K	B	F
VI	F	D	C	G	E	I	L	B	K	J	A	H
VII	L	H	E	J	B	K	A	I	D	G	F	C
VIII	B	A	D	H	I	L	K	J	F	C	G	E
IX	J	K	H	A	G	D	F	E	I	B	C	L
X	K	G	F	D	J	B	E	C	H	L	I	A
XI	G	L	I	E	C	A	H	K	J	F	D	B
XII	E	F	B	K	L	H	C	D	A	I	J	G

System of Replication:
Latin Square.

Area of each Plot:
1-400th acre.

Dusting Period:
July 14 to Aug. 14, 1930.

KEY TO TREATMENTS

Rate of sulphur dust per application per acre pounds	A	B	C	D	E	F	G	H	I	J	K	L
	Interval between dustings in days											
	21	14	7	4–3	3–2	14	7	4–3	14	7	4–3	0
0												X
15	X	X	X	X	X							
30						X	X	X				
45									X	X	X	

SUMMARY OF RESULTS

Treatment symbol	Total number of dustings	Per cent stem rust severity	Yield per acre bushels	Weight per bushel pounds	Grade	Increase in yield per acre over check bushels
A	2	88	7·5	42	Feed	1·4
B	3	81	8·2	43	"	2·1
C	5	60	14·2	55	#4	8·1
D	9	29	20·0	59	1°	13·9
E	15	23	25·9	59	1°	19·8
F	3	77	9·8	45	Feed	3·7
G	5	43	18·1	55	3°	12·0
H	9	8	27·8	61	1 Hard	21·7
I	3	74	10·7	49	#6	4·6
J	5	32	21·7	60	1°	15·6
K	9	5	30·4	61	1 Hard	24·3
L	–	95	6·1	40	Feed	–

Standard error of one treatment=0·68
Minimum significant yield difference=2·04 bushels per acre.

YIELD ANALYSIS OF VARIANCE

Source of variance	Sums of squares	Degrees of freedom	Variance of mean square	$\frac{1}{2}\log_e$
Rows	131·04	11	11·91	–
Columns	184·97	11	16·81	–
Treatments	9,021·57	11	820·14	3·3547
Error	621·01	110	5·64	0·8649
Total	9,958·59	143		$Z=2\cdot4898$

5% point=0·3136

If dusting is to become a practical method of rust control it must yield a net profit to the grower. Undoubtedly, the cost of sulphur dust will be the most important single factor in determining the practical value of this method. It is essential, therefore, to determine the minimum amount of sulphur that will control rust even under conditions most favourable for its development. It should be pointed out that the objective in these studies is not the most perfect control of rust but rather that degree of control which would give the greatest net return from the operation. The results of the present tests should be examined with this object in mind.

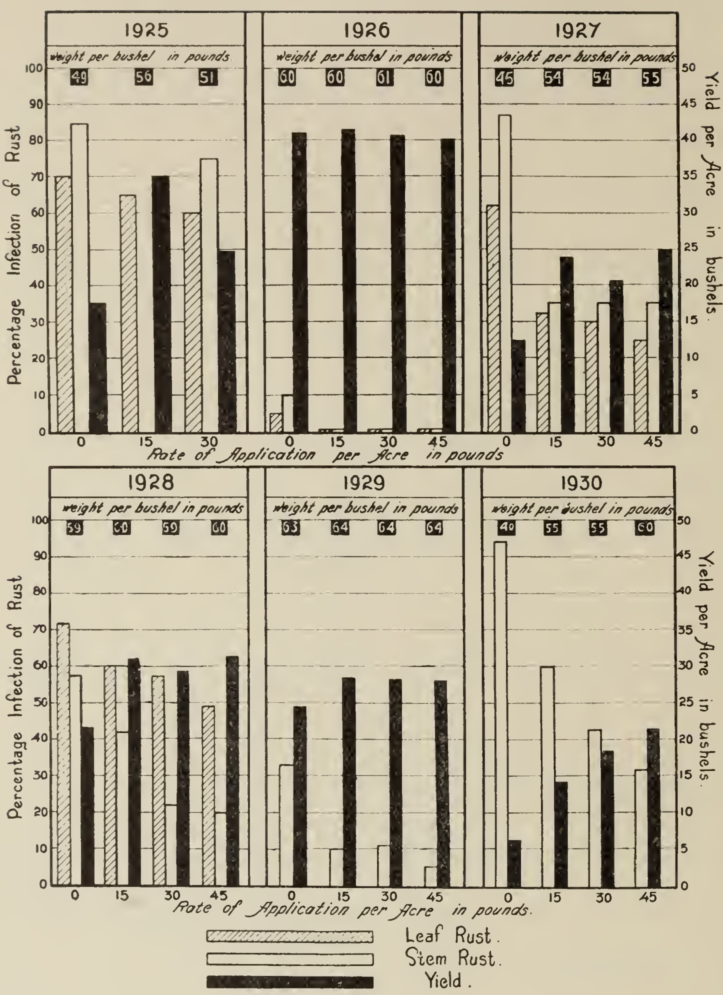

FIG. 14.—Effect of rate of sulphur dust application on the amount of leaf rust and stem rust infection, and on the consequent yield, and weight per bushel of grain in plots at Winnipeg. Results of dusting Marquis wheat at different rates and at 7-day intervals during the 6 years, 1925-1930.

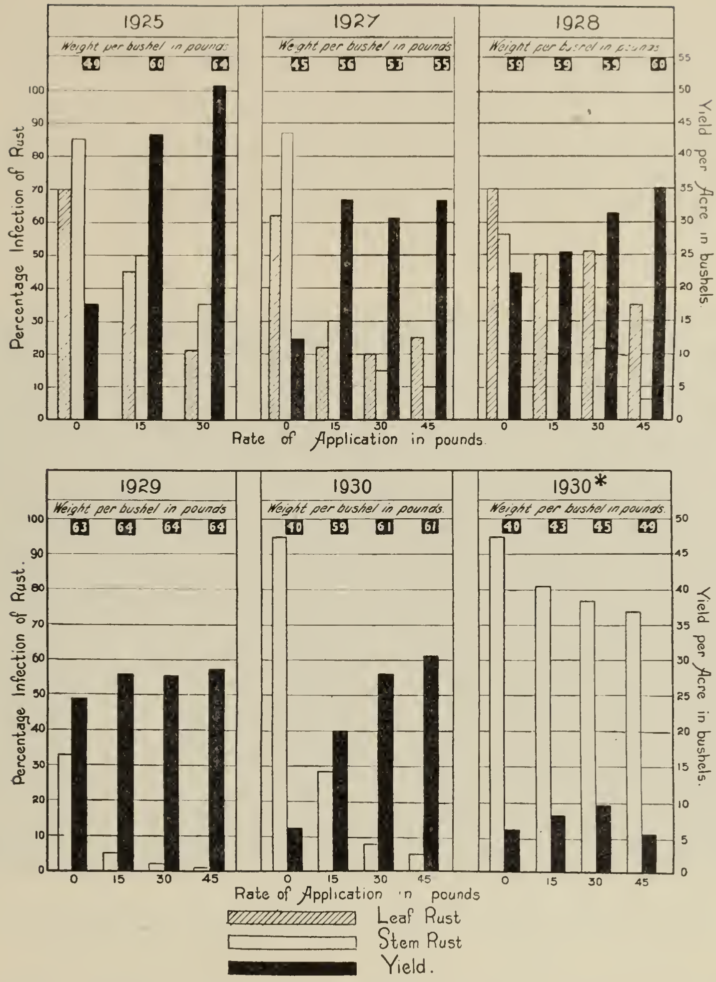

FIG. 15.—Effect of rate of sulphur dust application on the amount of leaf rust and stem rust infection, and on the consequent yield and weight per bushel of grain in plots at Winnipeg. Results of dusting Marquis wheat at different rates and at 3 to 4-day intervals in 1925, 1927, 1928, 1929, and 1930.

*(Interval between dust applications 14 days.)

The results presented in tables 25 to 28 indicate clearly that leaf rust and stem rust of wheat can be effectively prevented by dusting the growing plants with sulphur, even under conditions of severe natural epidemics. In all the tests there was a greater degree of rust control and a progressive increase in yield as the rate of dust application was increased. In 1925, 1927, and 1930, severe rust years, 30-pound applications of Kolodust gave excellent results. In 1930 nine 30-pound dustings increased the yield of Marquis wheat 21·7 bushels per acre and markedly improved the quality of the grain. A similar number of 45-pound dust applications in 1930 increased the yield 24·5 bushels per acre, or approximately 400 per cent. However, although the most perfect control of rust was achieved in 1930 by 45-pound dustings, the consequent increase in yield and grain quality was not great enough to cover the extra cost of the heavier dust application. A photograph of dusted and undusted plots of Marquis wheat grown at Winnipeg, in 1930, is shown in figure 16.

Fig. 16.—Plots of Marquis wheat at Winnipeg in 1930. Left: sulphur dusted plot. Right: check plot, not dusted, showing effect of severe stem rust attack.

It may be concluded from the six years results that the degree of rust control, and the consequent improvement in yield and grade, are direct functions of the rate of sulphur dust application. In order to insure satisfactory rust control, the rate of application will have to be decided each season according to the prevailing environmental conditions and the severity of the rust epidemic, as well as by the interval between applications, the means employed to apply the dust, and by the extent of control already achieved. Moreover, the most suitable rate of application for the control of leaf and stem rusts of wheat will vary from season to season in different regions. In light rust years, like 1926, 1928, and 1929, it would be most profitable to apply sulphur at the rate of 15 pounds per acre, and at intervals of 7 days; but, in bad rust years, like 1925, 1927, and 1930, the results indicate that 30-pound applications applied at intervals of 3 or 4 days would be the most effective treatment.

Interval Between Dust Applications

Sufficient evidence was obtained from greenhouse dusting tests to show that, under relatively dry conditions, finely-divided sulphur will adhere to foliage of cereal plants for a considerable length of time. When dusted plants were exposed to humid conditions, especially to showers of water, the adhesiveness and consequently the fungicidal efficiency of sulphur was greatly diminished. It seemed necessary therefore, to determine by field experiments the most satisfactory interval between dust applications, and to select a dusting interval which would give the maximum amount of protection for the minimum number of dust applications. In other words, to determine an interval which would afford consistent rust control under ordinary weather conditions.

Theoretically, it is possible to determine the most suitable interval between dust applications under any one set of seasonal conditions. Nevertheless, seasonal differences make it almost impossible to devise a practical dusting program for cereal rust control which would be equally effective each year and in all parts of the spring-wheat area. In this respect the problem is no different from any other dusting and spraying problem.

TABLE 29.—Influence of interval between dust applications. Effect of dusting Marquis wheat with sulphur at the rate of 15 pounds per acre per application on the amount of leaf and stem rust infection, yield, and quality of grain at Winnipeg in 1925, 1926, 1927, and 1928.

Year and duration of dusting period	Interval between dust applications days	Total number of dustings	Per cent leaf rust severity	Per cent stem rust severity	Yield per acre bushels	Weight per bushel pounds	Grade	Yield increase per acre over check bushels
1925*	0	0	70	85	17·7	49	Feed	–
July 2 to Aug. 25..	14	4	75	75	24·5	48	"	6·8
	7	8	65	60	35·1	56	3°	17·4
	3 to 4	17	45	50	43·1	60	2°	25·4
	2 to 3	24	15	5	55·1	63	1°	37·4
1926	0	0	5	10	41·6	60	1°	–
July 5 to Aug. 6...	7	5	tr	tr	43·2	60	1°	1·6
	3 to 4	11	tr	tr	42·8	61	1°	1·2
	2 to 3	15	tr	tr	45·1	61	1°	3·5
1927*	0	0	62	87	12·2	45	Feed	–
July 18 to Sept. 9..	14	4	42	75	15·4	46	"	3·2
	7	8	32	35	23·4	54	#5	11·2
	3 to 4	16	22	30	33·3	56	#4	21·1
	2 to 3	24	21	20	39·2	60	3°	27·0
1928	0	0	72	57	22·0	59	2°	–
July 17 to Aug. 29.	7	6	60	42	31·2	60	2°	11·2
	3 to 4	12	50	20	25·4	59	2°	3·4

*Severe rust years.

The effect of dusting Marquis wheat with sulphur dust at the rate of 15 pounds per acre at various intervals on the amount of rust infection, and on the consequent yield and quality of the grain at Winnipeg in 1925, 1926, 1927, and 1928, is shown in the data summarized in table 29. The results in table 30 show the effect on rust control of dusting at various intervals at the rate of 30 pounds per acre. As might be expected the results in tables 29 and 30 agree closely. The most satisfactory control of rust was achieved when the dust fungicide was applied at the closest intervals. This, of course, necessitated the largest number

of applications. In 1925, 1927, and 1930, rust epidemic years, effective results were obtained when the interval was from 2 to 3 days. The degree of rust control the weight per bushel, yield, and grade, were highest in plots so dusted. Graphs showing the effect of interval between dust applications on rust control, and on the yield and weight per measured bushel of Marquis wheat in each of the six years, 1925 to 1930, are presented in figures 17 and 18.

TABLE 30.—Influence of interval between dust applications. Effect of dusting Marquis wheat with sulphur at the rate of 30 pounds per acre per application on the amount of leaf and stem rust infection, yield, and quality of grain at Winnipeg, in 1925, 1927, and 1928.

Year and duration of dusting period	Interval between dust applications days	Total number of dustings	Per cent leaf rust severity	Per cent stem rust severity	Yield per acre bushels	Weight per bushel pounds	Grade	Yield increase per acre over check bushels
1925*	0	0	70	85	17·7	49	Feed	–
July 2 to Aug. 25..	14	4	75	80	20·3	50	"	2·6
	7	8	60	75	24·7	51	#4	7·0
	3 to 4	17	20	35	50·8	64	1°	33·1
1927*	0	0	62	87	12·2	45	Feed	–
July 2 to Aug. 25..	14	4	53	65	15·5	48	"	3·3
	7	8	30	35	20·6	54	#5	8·4
	3 to 4	16	20	15	30·5	53	#5	18·3
	2 to 3	24	20	8	42·6	54	#5	30·4
1928	0	0	71	57	22·0	59	2°	–
July 17 to Aug. 29.	7	6	51	22	29·1	59	2°	7·1
	3 to 4	12	51	12	31·2	59	2°	9·2

*Severe rust years.

In all of the tests the degree of rust control, and the consequent improvement in yield and grain quality, were a direct function of the frequency of dust application. It would seem that the interval between dust applications is a more important factor in determining the effectiveness of dust treatments than is the rate of application. From the results given in tables 25 to 30, it appears that in severe rust years, like 1925, 1927, and 1930, particularly for the control of leaf rust of wheat, relatively light sulphur applications made at short intervals will give the most effective rust control. It must be realized, however, that the cost of any treatment requiring three applications of dust each week for a dusting period which in Manitoba would be from four to six weeks is entirely prohibitive. Two applications per week might be considered feasible if the results obtained thereby were decidedly better than those obtained by one application per week. From the results of this investigation it would seem that in a bad rust year, dusting at 3 to 4-day intervals would be an effective and profitable practice.

It is extremely difficult to generalize as to what period constitutes the most suitable interval between sulphur dust application for the control of rust. In an ordinary year dusting at the rate of 30 pounds per acre, and at 7-day intervals, commencing when the first pustules of rust appear and continuing until the plants are beginning to ripen, should give very satisfactory rust control. Besides, this program is far more practical than one in which heavy applications are given at short intervals. In Manitoba, in an ordinary year, the maximum period of time between dust applications would be 7 days. It is well to realize that, to a great extent, the time elapsing between dustings will have to be decided from year to year according to the severity of the rust attack and the prevailing weather conditions, consideration always being given to the rate of application and the extent of control already achieved.

In years when severe outbreaks of rust occur, the plants must be protected with sulphur during the period when they are exposed to the attack of rust. In Manitoba, this period will be from four to six weeks. One or two timely dust applications might prove very efficacious but, even in severe rust years, 30 pounds of sulphur per acre, applied properly, and at intervals of from 5 to 7 days, will insure effective, practical, and economic control of stem rust of wheat and will reduce by a significant degree the amount of leaf rust.

Relative Effectiveness of Various Dust Fungicides

The testing of fungicides in the field to determine their toxic properties is an important phase of disease control work. Due, in part at least, to the ever-increasing number of proprietary compounds on the market, it is almost prohibitive in time and labour to make field tests of all the available commercial

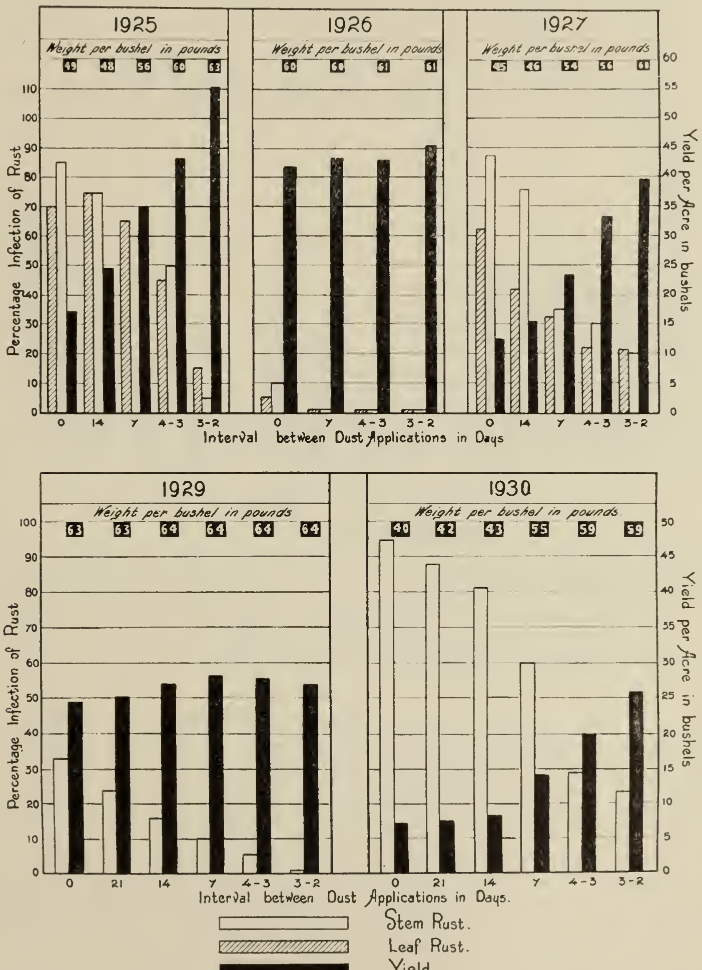

FIG. 17.—Effect of interval between sulphur dust application on the amount of leaf rust and stem rust infection, and on the consequent yield, and weight per bushel of grain, in plots at Winnipeg. Results of dusting at various intervals, and at the rate of 15 pounds per acre in 1925, 1926, 1927, 1929, and 1930.

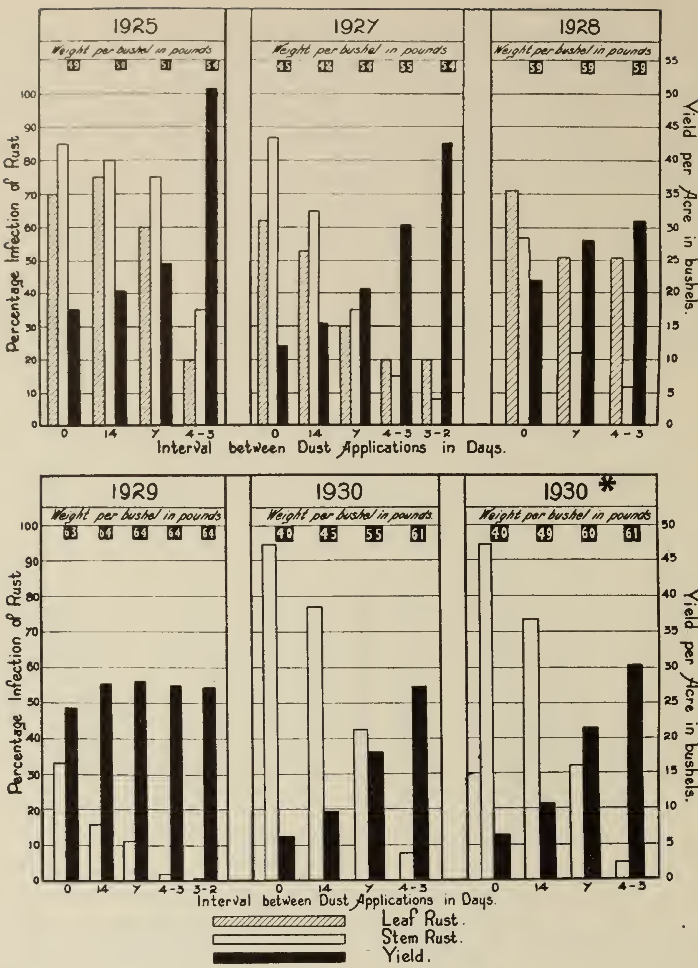

FIG. 18.—Effect of interval between dust applications on the amount of leaf rust and stem rust infection, and on the consequent yield, and weight per bushel of grain in plots at Winnipeg. Results of dusting Marquis wheat at various intervals, and at the rate of 30 pounds per acre in 1925, 1927, 1928, 1929, and 1930.
*(Rate of dust application 45 pounds per acre.)

compounds. In view of this fact, adequate greenhouse tests were relied upon to eliminate all but the most promising dust fungicides. From a great number of dusts, a few were selected for actual field trials.

As the cost as well as the fungicidal value of the dusts are important factors in determining their practical value for the control of cereal rusts, it seemed advisable to study the relative value of different commercial dusting compounds so that the most effective and economical fungicide could be used in practical field dusting tests. Field trials were made in 1928, 1929, and 1930 to determine the relative value of a representative group of available brands of dust fungicides.*

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* Kolodust and Sulfodust, manufactured by Niagara Sprayer and Chemical Co., Middleport, N.Y.; Electric Sulphur and Owl Sulphur by Stauffer Chemical Co., Houston, Texas, U.S.A.; Sulphur (300-mesh), Sulphur (200-mesh), National Sulphur Co., New York City, U.S.A.; Koppers sulphur dust prepared by the Koppers Research Corp., Pittsburg, Pa., U.S.A.; Koppers lime-sulphur dust obtained from Prof. H. W. Anderson, University of Illinois, Urbana, Ill., U.S.A.; Gas Dust from Dr. S. Karrer, Consolidated Gas, Electric Light and Power Co., Baltimore, Md., U.S.A.; and Tweddle's Dust, prepared by Mr. J. Tweddle, Hamilton, Ont.

The test consisted of applying the dry fungicides to plots of Marquis wheat, the treatments being replicated several times. The dusts were applied at the rate of 30 pounds per acre at 7-day intervals during the dusting period, the length of which was 42 days in 1928, 35 days in 1929, and in 1930 31 days.

The relative effect of the various dusts on the amount of stem rust at Winnipeg in 1928 and 1929, is shown in tables 31 and 32. From a study of these data, it is evident that Kolodust, Koppers lime-dust, Electric sulphur, Sulfodust, and Koppers dust gave exceptionally good rust control. Yields were increased to a significant degree and the grade was improved.

TABLE 31.—Relative fungicidal effectiveness of various sulphur dusts. Effect of six weekly dustings at the rate of 30 pounds per acre per application on the percentage of leaf and stem rust infection, and on the consequent yield, and quality of Marquis wheat, in 1928. (Dusting period—July 18 to Aug. 29).

Fungicide	Per cent leaf rust at harvest	Per cent stem rust at harvest	Yield per acre bushels	Weight per bushel pounds	Grade	Increase in yield per acre over check bushels
Kolodust	58	23	29·3	60	2°	6·8
Koppers dust	59	20	30·8	60	2°	8·3
Electric sulphur	60	20	33·2	59	2°	10·7
Sulphur (300 mesh)	64	30	27·0	58	2°	4·5
Sulphur (200 mesh)	70	50	24·2	58	2°	1·7
Check (no dust)	75	56	22·5	57	3°	–

Five 30-pound weekly treatments of Kolodust in 1929 reduced the amount of rust infection from 71 to 39 per cent and increased the yield by 9·7 bushels per acre. In 1930 none of the dusts, with the exception of Koppers dust, gave very effective rust control when applied at the rate of 30 pounds per acre and at 7-day intervals from July 14 to August 14 (table 33). From table 33 it will be seen that in this experiment the standard error of the mean yields for the respective treatments is 0·58.

TABLE 32.—Relative fungicidal value of six brands of sulphur dust. Effect of dusting wheat at the rate of 30 pounds per acre at 7-day intervals in late-sown plots on the amount of stem rust, and on the yield, and quality of Marquis wheat, at Winnipeg. (Dusting period—July 10 to August 14, 1929).

SUMMARY OF RESULTS

Fungicide	Per cent stem rust severity at harvest	Yield per acre bushels	Weight per bushel pounds	Grade	Increase in yield per acre over check bushels
Kolodust	39	34·4	63	1°	9·7
Koppers dust	56	29·3	62	1°	4·6
Electric sulphur	52	31·7	62	1°	7·0
Koppers+30% lime	56	32·6	62	1°	7·9
Gas dust	65	26·3	60	2°	1·6
Sulfodust	51	31·8	63	1°	7·1
Check (no dust)	71	24·7	56	#4	–

Standard error of one treatment = 1·53.
Minimum significant yield difference = 4·6 bushels per acre.

Yield Analysis of Variance

Source of variance	Sums of squares	Degrees of freedom	Variance of mean square	½ $\log_e$
Rows	221·20	6	36·87	–
Columns	1,260·28	6	210·05	–
Treatments	520·05	6	86·68	2·2311
Error	399·37	30	13·31	1·2867
Total	2,400·90	48	–	$Z=0\cdot9444$

5% point=0·4420

TABLE 33.—Relative fungicidal value of several sulphur dusts. Effect of five weekly dustings at the rate of 30 pounds per acre per application, on rust infection, yield, and quality of Marquis wheat in 1–200th acre plots in a Latin Square, at Winnipeg. (Dusting period—July 14 to August 14, 1930).

Summary of Results

Fungicide	Per cent rust severity at harvest	Yield per acre bushels	Weight per bushel pounds	Grade	Increase yield per acre over check bushels
Kolodust	57	8·6	47	6	2·8
Koppers dust	41	15·0	54	5	9·2
Electric dust	63	10·0	46	Feed	4·2
Koppers+30% lime	57	10·9	48	"	5·1
Sulfodust	65	8·6	46	"	2·8
Tweddle's dust	79	6·6	39	"	0·8
Kolodust+2% $KMnO_4$	76	7·9	42	"	2·1
Kolodust+5% $KMnO_4$	72	7·4	42	"	1·6
Owl dust	76	7·9	42	"	2·1
Check (no dust)	95	5·8	38	"	–

Standard error of one treatment=0·58.
Minimum significant yield difference=1·74 bushels per acre.

Yield Analysis of Variance

Source of variance	Sums of squares	Degrees of freedom	Variance of mean square	½ $\log_e$
Rows	194·74	9	21·64	–
Columns	54·80	9	6·09	–
Treatments	593·23	9	65·91	2·0941
Error	241·24	72	3·35	0·4473
Total	1,084·01	99	–	$Z=1\cdot6468$

5% point=0·3484

Examining the individual results in the light of their standard error, it was found that most of the ordinary commercial dusts had yield differences exceeding the limit set for significance. Koppers dust was definitely better than any of the others. The age of the Kolodust may have had something to do with its reduced fungicidal efficiency. How age effects the efficiency of dust fungicides requires further investigation. Tweddle's dust, a lime-sulphur mixture, did not control rust satisfactorily. The oxidized sulphur compounds were not so efficient as the ordinary finely-divided sulphur dusts.

The experimental evidence shows that, in so far as the control of leaf rust and stem rust of wheat are concerned, dusting with finely-divided sulphur constitutes an effective control measure, and that refined sulphur dusts are superior to the coarser brands. The low-priced, medium grades of sulphur dust give very satisfactory rust control, and from an economic viewpoint, may prove extremely valuable.

Oxidized sulphur dusts.—The work of Lee and Martin (55) suggested experiments to determine the value of oxidized sulphur dusts for cereal rust control. Bailey and Greaney (4), in 1927, obtained slightly better control of stem rust on wheat with Kolodust to which one per cent of potassium permanganate had been added as an oxidizing agent than with unoxidized Kolodust. The difference, however, was not very striking and further experiments were desirable. In a more recent report, Lee and Martin (56) have suggested that the control of some of the diseases of crops, other than sugar cane, might be made more effective and economical by the use of these oxidized sulphur mixtures. In order to obtain more definite information concerning the value of oxidized sulphur dusts for the control of cereal rusts, the field tests were continued in Manitoba in 1928, 1929 and 1930.

Plots of Marquis wheat were dusted at the rate of 30 pounds of dust per acre, and at 7-day intervals, from the time rust first appeared until the crop was ripening. Six weekly applications were made in 1928; five in 1929 and 1930. In these experiments, one series of plots was dusted with ordinary Kolodust, another with Kolodust to which 2 per cent of finely-divided potassium permanganate (300-mesh) had been added as the oxidizing agent, and a third series was treated weekly with a mixture of 5 per cent potassium permanganate in sulphur. A proprietary oxidized sulphur dust* was included in the test in 1929. The plots were sufficiently replicated, and an adequate control series of undusted plots was used. The results of the three years' trials are given in table 34.

TABLE 34.—Relative fungicidal effectiveness of oxidized sulphur dusts. Effect of weekly dustings at the rate of 30-pound per acre per application, on the amount of leaf rust and stem rust, and on the consequent yield and quality of Marquis wheat, in 1928, 1929, and 1930.

Year	Fungicides	Per cent leaf rust severity	Per cent stem rust severity	Weight per bushel pounds	Yield per acre bushels	Increase in yield per acre over check bushels
1928	Kolodust	51	22	60	29·1	6·7
July 17 — Aug. 29	Kolodust+2% $KMnO_4$	48	25	59	29·0	6·6
	Kolodust+5% $KMnO_4$	50	25	59	28·2	5·8
	Check (no dust)	71	57	59	22·4	–
1929	Kolodust	15	41	64	39·3	16·7
July 9—Aug. 10	Kolodust+2% $KMnO_4$	18	60	61	29·3	6·7
	Kolodust+5% $KMnO_4$	15	56	62	32·7	10·1
	Grade A dust	20	63	61	29·2	6·6
	Check (no dust)	20	72	56	22·6	–
1930	Kolodust	30	57	44	8·6	2·8
July 14—Aug. 14	Kolodust+2% $KMnO_4$	32	76	42	7·4	1·6
	Kolodust+5% $KMnO_4$	30	72	42	7·9	2·1
	Check (no dust)	35	95	38	5·8	–

Standard error of one treatment. 1929=1·94; 1930=0·58.
Minimum significant yield difference (bushels per acre). 1929=5·8; 1930=1·7.

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* Oxidized sulphur dust Grade A prepared by the Stauffer Chemical Co., San Francisco, Cal., U.S.A., under the patent of Atherton H. Lee and J. P. Martin.

In 1928 all of the dusts gave very satisfactory stem rust control, but leaf rust development was not checked significantly by any of the weekly treatments. Excellent results were obtained in 1929 with Kolodust, but none of the oxidized dusts prepared in the laboratory were so efficient protectants as was unoxidized sulphur dust. The commercially prepared oxidized sulphur was not so effective as Kolodust. Similar results were obtained in 1930. The results of the three years' tests do not show that there is any particular advantage in using oxidized sulphur dusts for the control of cereal rusts.

Effect of Initial Time of Dusting

In the experiments already described, successful prevention of rust was obtained when the growing plants were first dusted just as soon as stem rust appeared in the Winnipeg district, but not necessarily in the experimental plots. The first appearance of rust in a district would be the most satisfactory criterion as to when dusting in that district should be commenced, but it can only be employed if the development of rust is watched closely by trained observers. If the first appearance of rust could be definitely correlated with a certain growth stage of the wheat plant it would be a convenient guide as to when to commence dusting, but this correlation is difficult to establish. Lambert and Stakman (54), and Broadfoot (12), arbitrarily selected the flowering stage as the time to start dusting operations on wheat in Minnesota for the control of stem rust.

TABLE 35.—Effect of time at which dusting is commenced on the amount of leaf rust and stem rust infection, and on the consequent yield and quality of Marquis wheat at Winnipeg, in 1927 and 1928.

Year and dusting period	Treatment symbol	Date of initial dust application	Per cent leaf rust severity at harvest	Per cent stem rust severity at harvest	Yield per acre bushels	Weight per bushel pounds	Increase in yield per acre over check bushels
	D	July 18	32	35	33·4	54	21·2
	E	" 25	45	65	26·4	51	14·2
	F	Aug. 8	40	65	17·9	49	5·7
	N	Check	63	87	12·2	45	–
1927	L	July 18	25	35	25·0	56	12·8
	M	Aug. 15	65	65	13·5	44	1·3
July 18 — Sept. 9	N	Check	63	87	12·2	45	–
	A	July 18	22	30	33·3	56	21·1
	B	" 25	45	45	24·6	54	12·4
	C	Aug. 8	60	60	13·5	47	1·3
	N	Check	63	87	12·2	45	–
	K	July 18	25	10	33·4	53	21·2
	L	Aug. 15	60	65	14·3	46	2·1
	N	Check	63	87	12·2	45	–
	G	July 25	60	32	24·6	58	4·6
1928	H	Aug. 1	65	33	25·9	59	5·9
	I	" 8	67	37	23·1	59	3·1
July 17 — Aug. 29	J	" 15	67	42	21·2	57	1·2
	N	Check	75	65	20·0	57	–

KEY TO TREATMENTS

Rate of dust per acre per application in pounds	A	B	C	D	E	F	G	H	I	J	K	L	M	N
	Total number of dust applications													
	16	14	10	8	7	5	6	5	4	3	16	8	4	0
0														X
15	X	X	X	X	X	X								
30							X	X	X	X				
45											X	X	X	

In 1927, 1928, 1929, and 1930, experiments were carried out at Winnipeg to determine how late dusting could be begun and yet be effective in controlling rust. In these studies, the initial dust applications were made at different stages in the development of the stem rust epidemic, and thereby at different growth stages of the plant.

The results for 1927 and 1928 are given in table 35, while those for 1929 and 1930 are summarized in tables 36 and 37. The four years' results are presented graphically in figure 19.

TABLE 36.—Effect of time dusting is commenced on the amount of stem rust infection, and on the consequent yield and quality of grain. Results of dusting Marquis wheat at the rate of 30 pounds per acre per application, and at 7-day intervals, at Winnipeg. (Dusting period—July 10 to August 14, 1929).

SUMMARY OF RESULTS

Date of initial dust applications	Total Number of dustings	Per cent stem rust severity		Yield per acre bushels	Weight per bushel pounds	Grade	Increase in yield per acre over check bushels
		At time of initial dusting	At harvest				
July 10	6	trace	29	28·1	64	2°	8·0
" 17	5	tr– 5	21	28·5	63	2°	8·4
" 24	4	10–20	37	24·7	60	3°	4·6
' 31	3	20–24	51	20·7	61	3°	0·6
Check	0	–	60	20·1	60	3°	–

Standard error of one treatment=1·63.
Minimum significant yield difference=4·9 bushels per acre.

YIELD ANALYSIS OF VARIANCE

Source of variance	Sums of squares	Degrees of freedom	Variance of mean square	$\frac{1}{2}\log_e$
Rows	102·11	4	25·53	–
Columns	41·40	4	10·35	–
Treatments	310·57	4	77·64	2·1760
Error	158·62	12	13·22	1·2908
Total	612·70	24		Z=0·8852

5% point=0·5371

From the 1927 data it will be noticed that the most effective control of stem rust was achieved when the initial dust applications were made on July 18. At this time approximately 50 per cent of the wheat plants were in head.

and rust was beginning to appear in the Winnipeg district. By delaying dusting until July 25 three applications of sulphur per week were required subsequently to obtain the same measure of control as was achieved by the weekly applications in the series of plots which were dusted on July 18. By August 8, 90 per cent of the plants were infected with a trace to 20 per cent of stem rust. The series of plots which received no sulphur application until August 8 but subsequently were dusted at the rate of 45 pounds per acre twice each week until the crop was ripening, failed to give satisfactory results. Plot experiments, similar to the 1927 experiment, were made in 1928, 1929, and 1930.

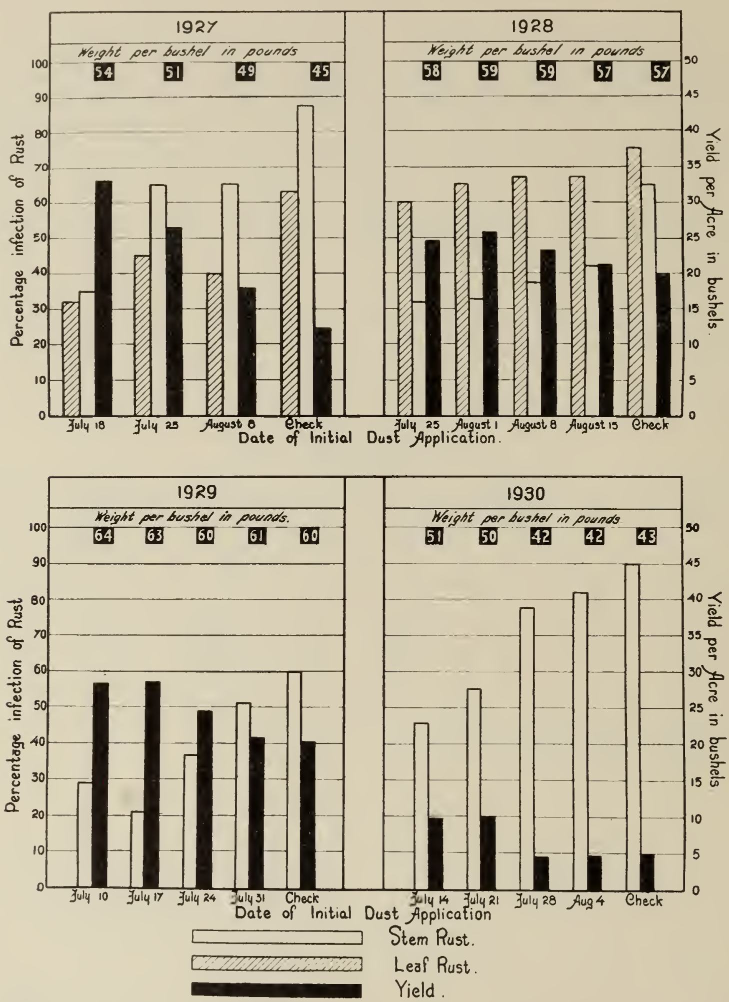

Fig. 19.—Effect of initial time of sulphur dust application on the amount of leaf rust and stem rust at harvest, and on the consequent yield and weight per bushel of grain in plots at Winnipeg. Results of dusting Marquis wheat at 7-day intervals, and at the rate of 30 pounds per acre in 1928, 1929, and 1930. In 1927 the rate of application was 15 pounds per acre.

An examination of the experimental data in tables 35, 36, and 37 shows that in each year there was a very definite response to early dust application. The results emphasize the importance of having cereal plants well protected with sulphur before inoculum becomes plentiful.

TABLE 37.—Effect of time dusting is commenced on the amount of stem rust infection, and on the consequent yield and quality of grain. Results of dusting Marquis wheat with sulphur at the rate of 30 pounds per acre per application, and at 7-day intervals, at Winnipeg, in 1930. (Dusting period—July 14 to August 12, 1930).

SUMMARY OF RESULTS

Date of initial dust application	Total number of dustings	Per cent stem rust severity		Yield per acre	Weight per bushel	Grade	Increase in yield, per acre over check
		At time of initial dusting	At harvest	bushels	pounds		bushels
July 14	5	trace	46	9·8	51	Feed	4·8
" 21	4	tr- 5	55	10·0	50	"	5·0
" 28	3	24–40	78	4·5	42	"	–
Aug. 4	2	30–55	82	4·6	42	"	–
Check	0	–	90	5·0	43	–	–

Standard error of one treatment=0·83.
Minimum significant yield difference=2·49 bushels per acre.

YIELD ANALYSIS OF VARIANCE

Source of variance	Sums of squares	Degrees of freedom	Variance of mean square	$\frac{1}{2}\log_e$
Rows	45·64	4	11·41	–
Columns	68·26	4	17·06	–
Treatments	163·58	4	40·90	1·8555
Error	51·66	12	4·30	0·7293
Total	329·14	24	....	$Z=1\cdot1262$

5% point=0·5907

In Manitoba where Marquis wheat is grown extensively, the first appearance of stem rust is fairly closely correlated with the late "boot" or early heading stage of plant growth. Each year, during the six-year period 1925-1930, stem rust of wheat did not appear on the experimental plots until after from 10 to 50 per cent of the wheat plants were in head. From observations made over a much longer period, it would seem that in the spring-wheat region of Western Canada stem rust, as a rule, does not become established and abundant until the majority of the plants are in head. In order to insure satisfactory stem rust control, it is advisable, in Manitoba, to commence dusting Marquis wheat when about 50 per cent of the plants are in head. Seasonal differences make it impossible to give a definite date which would hold good for all seasons and in all regions.

Leaf rust of wheat appears in Manitoba much earlier than does stem rust, and hence dusting for the control of this disease is a more difficult problem than dusting for stem rust control. It is necesary to keep a careful watch for the early development of leaf rust and to dust the plants first when rust first appears in a district.

The time at which dusting can be safely discontinued will depend on the amount of rust present in the dusted crop, the prevailing weather conditions, and the stage of plant growth. The results of the present experiments indicate that it is advisable to protect the plants almost to the time of ripening.

Method of Dust Application

Preliminary field tests with hand, horse-drawn, and aeroplane dusters demonstrated clearly the value of thoroughly dusting the whole surface of the

plants with sulphur. Furthermore, during the course of these experiments, the necessity of forcibly applying dry sulphur to the growing plants was clearly demonstrated. In 1927 particularly, it was observed that the fungicidal efficiency of sulphur was considerably reduced and a waste of material occurred when the dust was allowed to drift over and settle down on the standing crop.

TABLE 38.—Relative effect of different methods of dust application. Results of dusting with sulphur at the rate of 30 pounds per acre per application and at 7-day intervals, on the percentage of stem rust infection, and on the consequent yield and quality of Marquis wheat, in 1928, 1929, and 1930.

Year and dusting period	Method of treatment	Per cent stem rust severity at harvest	Weight per bushel pounds	Yield per acre bushels	Increase in yield per acre over check bushels
1928					
July 18 — Aug. 22	Dusting	36	58	17·9	2·9
	Drifting	45	56	16·2	1·2
	Check	62	55	15·0	–
1929					
July 9 — Aug. 13	Dusting	41	62	39·3	16·7
	Drifting	54	62	35·2	12·6
	Check	72	56	22·6	–
1930					
July 14 — Aug. 4	Dusting	49	51	13·1	8·0
	Drifting	74	43	8·0	2·9
	Check	92	38	5·1	–

Standard error of one treatment, 1929 = 1·94; 1930 = 0·14.
Minimum significant yield difference (bushels per acre), 1929 = 5·8; 1930 = 0·4.

Studies on the relative value of the direct dusting method, viz., applying sulphur forcibly on the growing plants, and the drifting method, were carried out at Winnipeg in 1928, 1929, and 1930. The experimental results for the three years are summarized in table 38. In 1928 the average severity of stem rust at harvest in plots dusted by the first method was 36 per cent, while there was 45 per cent in those plots dusted by the second method. The untreated plots had 65 per cent infection. The effectiveness of Kolodust was reduced when the dust was allowed to drift over and settle on the plants. Experiments in 1929 and 1930 gave similar results. In these years highly significant yield differences were obtained in favour of the dusting method. From the three years' results it is clear that increased protection was afforded the growing plants when the dust was applied forcibly to them.

Effect of Meteorological Conditions on Dusting

The effectiveness of sulphur dusting for the control of cereal rusts is very appreciably influenced by meteorological conditions. The results of some preliminary tests conducted in 1925 by Bailey and Greaney (2) indicated that the most satisfactory control of leaf rust and stem rust of wheat was obtained when the time of applying the dust was chosen with reference to certain weather conditions. It was found that seven weekly 15-pound dustings of sulphur applied irrespective of weather conditions were not nearly so effective as the same number of dustings made just before rains. This result suggested further experiments to determine the relative value of applying sulphur before rain and after rain.

Field experiments were made in 1928, 1929, and 1930, the results of which are given in table 39. Each year a certain number of plots were dusted before rains, and the same number of plots after rains. A check treatment in which

the same number of plots were dusted weekly, as well as an undusted check, were included in each experiment. It is clear from these experiments that the most satisfactory control of rust was obtained when the dust was applied immediately after rains while the plants were still damp. When the sulphur was applied before rain, the rain washed some of it off, thereby exposing parts of the plants to infection.

TABLE 39.—Effect of dusting Marquis wheat before and after rains at the rate of 30 pounds per acre per application, on the amount of rust infection, and on the consequent yield and quality of grain, at Winnipeg, in 1928, 1929, and 1930.

Year and dusting period	Treatment	Total number of dustings	Per cent stem rust severity at harvest	Yield per acre bushels	Weight per bushel pounds	Grade	Increase in yield per acre over check bushels
1928	Standard	7	30	23·4	59	2°	7·0
July 18 — Aug. 30	Before rain	4	35	19·4	56	3°	3·0
	After rain	5	25	22·3	58	2°	5·9
	Check	0	55	16·4	53	3°	–
1929	Standard	6	41	39·3	64	1 Hard	16·7
July 9 — Aug. 14	Before rain	3	57	30·0	60	1°	7·4
	After rain	3	46	39·0	64	1 Hard	16·4
	Check	0	72	22·6	56	3°	–
1930	Standard	4	49	13·1	51	#5	8·0
July 14 — Aug. 14	Before rain	3	63	6·9	43	Feed	1·8
	After rain	2	76	6·2	39	"	1·1
	Check	0	92	5·1	38	"	–

Standard error of one treatment, 1929 = 1·94; 1930 = 0·14.
Minimum significant yield difference (bushels per acre), 1929 = 5·8; 1930 = 0·4.

The effect of meteorological conditions on the effectiveness of dusting with sulphur for rust control was emphasized by the field experiments conducted at Winnipeg during the period 1925 to 1930. Distribution, coverage, and adhesiveness of sulphur dust were influenced by such meteorological factors as rain, dew, and wind. In the application of dry fungicides, wind is the greatest disturbing factor. The results indicated that dust applied in the early morning or late evening, when there was the least movement of air, afforded the plants the greatest protection against rust. It was observed also that the presence of dew on the plants caused the dust to adhere to them better.

Effect of Sulphur as a Fertilizer

In analyzing the results of the preliminary field experiments, it was thought that there might be some definite fertilizing effect of sulphur that would merit consideration in an interpretation of the yield data. Broadfoot (12) found there was no fertilizing effect by broadcasting Kolodust on the soil. Field experiments by Lobik (57), in 1929, showed that applications of a sodium arsenate spray to wheat considerably reduced the yield of grain, while sulphur dusting did not appreciably affect the yield. His experiments were primarily planned to test the controlling effect of these substances on rust, but no definite conclusions on this point were reached, owing to the slight incidence of rust.

In 1926 the small plot dusting experiment was not very satisfactory as a test of rust control but, due to the absence of significant amounts of rust, it

afforded a splendid opportunity to investigate the effect of sulphur dust on the yield of wheat. The data presented in table 25 show that there was no observable evidence of any fertilizing effect of sulphur, even when the growing plants were dusted five times with sulphur at the rate of 45 pounds per acre. In another series of plots to which fifteen 15-pound applications of sulphur were made, the average yield was not significantly different from those of the plots to which sulphur was not applied.

At Winnipeg, in 1927, Kolodust was applied directly to the soil between the drill rows of Marquis wheat. The first application of 45 pounds per acre was made when the plants were in the late "boot" stage of growth, and thereafter, similar amounts of sulphur were applied to the soil at 7-day intervals until the crop was ripening. Plots so treated were compared with plots in which the same amount of sulphur dust was applied directly to the growing plants. A third series was left untreated as check plots. The yield, weight per bushel, and grade of wheat of the soil-treated plots did not differ from those of the plots to which no Kolodust was applied; while there was a decided improvement in yield and quality of grain from the plots to which Kolodust was applied to the growing plants.

In this experiment there was a slight possibility that fumes of volatilized sulphur on the soil might act as a toxic agent to the rust and inhibit its development. The 1927 results gave no evidence of this. The percentage of stem rust on the plants in the soil-treated plots ranged from 65 to 90; while the range of rust in the untreated check plots was from 60 to 90 per cent. On the other hand, the average amount of stem rust on the plots dusted in the usual way was reduced to 30 per cent. It would seem that the amount of sulphur volatilized at any one time from the soil was wholly insufficient to influence the development of rust.

A mild rust epidemic developed at Winnipeg in 1929. In the absence of any considerable amounts of leaf and stem rust, there was no observable evidences of rust control, nor significant increases in yield, weight per bushel, or grade of wheat, even when sulphur was applied to the growing plants at the rate of 45 pounds per acre, and at intervals of 2 to 3 days from July 9 to August 10 (see table 27). That is, there was no observable fertilizing effect by applying as much as 765 pounds of sulphur per acre to the standing crop. From the results obtained in 1926, 1927, and 1929, it is concluded that dusting growing plants with sulphur had no fertilizing effect, and hence little, if any, direct influence on the yield of wheat.

THE PREVENTION OF CROWN AND STEM RUST OF OATS

Kightlinger's (49) preliminary studies on the use of fungicidal dusts in the control of rust were made on crown rust and stem rust of oats, (*P. coronata avenae* and *P. graminis avenae*). His results demonstrated the possibility of controlling rusts of oats by dusting. Laboratory and greenhouse experiments, mentioned earlier in this paper, on the inhibitory effects of several dust fungicides on the germination of aeciospores and urediniospores of *P. graminis avenae* and *P. coronata,* indicated that finely-divided sulphur dusts were effective fungicides against these rusts. Small plot experiments to determine the effectiveness and practicability of dusting with sulphur for their prevention, and to study the relation between rust infection and grain yield were carried out at Winnipeg in 1929 and 1930.

Experiments in 1929

In Manitoba, stem rust and crown rust of oats in 1929 were not severe, and oats in the experimental plots at Winnipeg were not appreciably damaged. At harvest time, rust and yield data were secured only from three of the ten series

of plots included in the Latin Square experiment. The effect of dusting on the amount of crown rust and stem rust infection, and on the consequent yield and quality of Victory oats in these plots, is shown in Table 40.

TABLE 40.—Results of sulphur dusting experiment for the prevention of oat rusts. Effect of rate and frequency of dust application on the amount of rust infection, and on the yield and quality of Victory oats in 1929, at Winnipeg, Man.

Amount of dust per acre, in pounds	Date dusted		Mean results of ten 1-400th acre plots				
	July	August	Per cent crown rust severity	Per cent stem rust severity	Weight per bushel in pounds	Yield per acre in bushels	Increase in yield per acre over check bushels
30	15, 22, 29	5	tr.	tr-5	37·5	64·6	5·6
45	15, 19, 22, 26, 29	2, 5, 9	tr.	tr.	37·5	65·1	6·1
Check	No dust	–	5	15	37·0	59·0	–

In 1929, a light rust year, crown rust and stem rust of oats were almost completely prevented by four 30-pound applications of Kolodust. As the season was not very favourable for the purpose of the study the investigation was continued in 1930, and field experiments were made on a more adequate scale than in 1929.

Experiments in 1930

In 1930, two experiments were designed to determine the smallest number of dustings that would control rusts of oats, the effect of different rates of application, and the most satisfactory interval between dustings. One experiment was made on stem rust, the other on crown rust. In these studies, different dust treatments gave different degrees of rust control. In the final analysis of the experimental data rust percentages of individual plots were correlated with yield.

The same dusting program was followed in each experiment. Kolodust was applied at three rates: 15, 30, and 45 pounds per acre at each application. At the 15-pound rate, applications were made at intervals of 14, 7, 3 to 4, and 2 to 3 days; and 45-pound applications, at 14-, and 7-day intervals. Dusting was begun on July 16, and, thereafter, the plots were treated at the intervals just indicated until August 25, at which time the oats were ripening. Final rust notes were taken on August 28 and the plots were harvested on August 31. Although a severe natural epidemic of oat stem rust occurred, there was no general infection of crown rust in the Winnipeg district in 1930. An epidemic of crown rust was produced artificially in the experimental plots.

Results of stem rust experiment.—The dusting schedule followed in the stem rust experiment together with the results showing the effect of sulphur dust on the amount of rust infection, and on the consequent yield and quality of Victory oats are given in Table 41.

TABLE 41.—Sulphur dusting experiment for the prevention of stem rust of oats. Effect of rate and frequency of dust application on the amount of rust, and on the yield and quality of Victory oats in 1–400th acre plots in a 10 x 10 Latin Square at Winnipeg, in 1930. (Dusting period—July 16 to August 25, 1930).

SUMMARY OF RESULTS

Treatment symbol	Per cent crown rust at harvest	Per cent stem rust at harvest	Yield per acre bushels	Weight per bushel pounds	Grade	Increase in yield per acre over check bushels
A	trace	52	57·4	32	2 Feed	11·1
B	"	25	62·1	37	1 "	15·8
C	"	15	65·9	35	1 "	19·6
D	"	6	68·6	36	1 "	22·3
E	trace	13	61·6	35	1 Feed	15·3
F	"	5	66·9	36	1 "	20·6
G	"	2	67·5	36	1 "	21·2
H	trace	32	62·7	33	1 Feed	16·4
I	"	9	66·4	35	1 "	20·1
J	tr–8	67	46·3	29	2 Feed	–

Standard error of one treatment = 3·01.
Minimum significant yield difference = 9·03 bushels per acre.

KEY TO TREATMENTS

Rate of sulphur dust per application per acre	A	B	C	D	E	F	G	H	I	J
	Interval between dustings in days									
pounds	14	7	4–3	3–2	7	4–3	3–2	14	7	0
0										X
15	X	X	X	X						
30					X	X	X			
45								X	X	

YIELD ANALYSIS OF VARIANCE

Source of variance	Sums of squares	Degrees of freedom	Variance of mean square	½ $\log_e$
Rows	3,459·51	9	284·39	–
Columns	689·54	9	76·62	–
Treatments	4,534·72	9	503·86	3·1113
Error	6,511·78	72	90·44	2·2521
Total	15,195·55	99		$Z = 0{\cdot}8592$

5% point = 0·3484

These results indicate clearly that, even in the presence of an epidemic, relatively small amounts of sulphur dust effectively checked the development of rust. There was a very significant response in yield to all the treatments. In every instance the gain in yield and quality of grain was more than enough to cover the cost of the treatment.

At any given dusting interval 15-pound applications of sulphur were as effective as 30- and 45-pound applications. The length of time elapsing between dust applications was a much more important factor in the control of rust than was the rate of dust application. The most effective stem rust control, and consequently the most satisfactory improvement in yield and quality of grain were obtained by applying 15 pounds of Kolodust per acre at intervals of two days from July 16 to August 22. The average yield of the ten undusted plots was 46.3 bushels per acre of No. 2 Feed Oats; whereas, the average yield of the ten plots so dusted was 68·6 bushels of No. 1 Feed Oats, an increase of 22.3 bushels per acre and a decided improvement in grain quality.

Results of the crown rust experiment.—The fact that in 1930 the oats in these experimental plots were heavily infected with stem rust as well as with crown rust complicated the problem of determining the actual effect of crown rust on the yield of oats, but produced excellent conditions for studying the effect of dusting on the control of these rusts. The results of the crown rust experiments are given in table 42.

TABLE 42.—Sulphur dusting experiment for the prevention of crown rust of oats. Effect of rate and frequency of dust application on the amount of crown rust and stem rust infection, and on the yield and quality of Victory oats in 1-400th acre plots in a 10 x 10 Latin Square at Winnipeg, in 1930. (Dusting period—July 16 to August 25, 1930).

SUMMARY OF RESULTS

Treatment symbol	Per cent crown rust at harvest	Per cent stem rust at harvest	Yield per acre bushels	Weight per bushel pounds	Grade	Increase in yield per acre over check bushels
A	52	53	37·9	29	2 Feed	8·4
B	32	26	53·5	32	1 "	24·0
C	20	12	58·1	34	1 "	28·6
D	3	3	71·8	34	1 "	42·3
E	21	10	62·9	34	1 Feed	33·4
F	11	3	64·8	35	1 "	35·3
G	1	tr	74·8	35	1 "	45·3
H	36	30	54·8	32	1 Feed	25·3
I	26	17	60·9	33	1 "	31·4
J	74	61	29·5	26	2 Feed	-

Standard error of one treatment = 2·39.
Minimum significant yield difference = 7·17 bushels per acre.

KEY TO TREATMENTS

Rate of dust per application	A	B	C	D	E	F	G	H	I	J
	Interval between dustings in days									
days	14	7	4–3	3–2	7	4–3	3–2	14	7	0
0	....	....	....	....	....	....	....	....	....	X
15	X	X	X	X	....	....	....	....	....	....
30	....	....	....	....	X	X	X	....	....	....
45	....	....	....	....	....	....	....	X	X	....

YIELD ANALYSIS OF VARIANCE

Source of variance	Sums of squares	Degrees of freedom	Variance of mean square	$\frac{1}{2}$ log$_e$
Rows	1878·85	9	208·76	–
Columns	544·04	9	60·45	–
Treatments	18442·38	9	2049·15	3·8132
Error	4121·62	72	57·24	2·0236
Total	24986·89	99	....	$Z = 1 \cdot 7896$

5% point = 0·3484

In this experiment the best crown rust control was achieved by 30-pound applications which were made at 2 to 3-day intervals (tri-weekly from July 16 to August 22). In plots so dusted both crown rust and stem rust were prevented to a marked degree, and the yield of Victory oats was increased 45 bushels per acre, about 153 per cent. Plots of dusted and undusted Victory oats grown at Winnipeg in 1930, are illustrated in figure 20.

FIG. 20.—Effect of controlling crown rust and stem rust of oats with sulphur dust in plots at Winnipeg in 1930. A. Dusted plants, clean peduncles and leaves with well-filled panicles. B. Check plants, heavily rusted with broken stems and small unfilled panicles.

From the 1930 results it would seem that, in a severe rust year, the most suitable rate of dust application would be 30 pounds per acre and the most effective interval between dustings from 2 to 5 days. However, this is not a very

practical treatment for rust control. The results obtained in 1929 and 1930 do not permit of a final conclusion regarding the most suitable rate and frequency of sulphur dust application.

Experiments in 1931

Sulphur dusting for the prevention of crown rust.—For the purpose of this study, a strain of oats from the cross, Hajira Strain x Banner, obtained from the Cereal Division, Dominion Rust Research Laboratory, was used. This strain was selected because of its high resistance to all the physiologic forms of oat stem rust which commonly occur in Canada, and its susceptibility to crown rust. Thus, by eliminating stem rust, it was hoped to control crown rust by sulphur and thereby be able to determine its effect on yield.

The strain was sown in rod rows, separated by buffer rows, and arranged in two series, each containing 15 dusted and 15 undusted rows. These series were so planted that adjacent dusted and undusted rows could be considered as pairs. The yield data were subjected to statistical analysis.

In table 43 are given the schedule for dusting and other experimental data on the amount of rust infection, yield, and weight of grain per bushel. From the data it is apparent that frequent applications of sulphur greatly reduced the amount of crown rust. The significance of the yield results between the paired rows was tested by the method given by Fisher (26). In determining the significance of the yield results; a t value of 2·05 was obtained. The odds of significance are greater than 20:1 as for these odds a t value of 2·04 is required. In 1931, a 45 per cent infection of crown rust reduced the yield 4·8 bushels per acre. This loss was prevented by dusting with sulphur.

TABLE 43.—Effect of dusting Victory oats with sulphur at the rate of 15 pounds per acre, per application on the amount of crown rust infection, on yield and quality, in rod rows, at Winnipeg, in 1931.

Treatment	Date rows dusted		Per cent crown rust at harvest	Yield per acre	Weight per bushel	Increase in yield per acre over check
	July	August		bushels	pounds	bushels
Dusted	10, 13, 16, 19, 22, 25, 28, 30.	1, 3, 5, 11, 13, 15.	9	44·4	34	4·8
Undusted (Check)	—	—	54	39·6	32	–

$t = 2 \cdot 05$. 5% point $= 2 \cdot 04$.

SULPHUR DUSTING FOR THE PREVENTION OF MINOR LEAF AND STEM DISEASES OF WHEAT

During the early part of the investigation it was observed that frequent applications of sulphur dust prevented the development of some of the minor diseases of wheat. From field observations made in 1925, 1926, and 1927 it was apparent that sulphur-dusted plants were cleaner in the straw, brighter in colour, and generally more healthy than those which remained unprotected during the growing season. In 1926 and 1928, light rust years, it was found, too, that differences in yield between dusted and undusted plots of Marquis wheat were due to factors operating in the absence of significant amounts of rust. These yield differences seemed to be associated closely with the presence of diseases caused by various leaf and stem spotting fungi, and suggested experiments to determine

the effect of sulphur in preventing their development. In the present studies particular attention was given to the prevention of wheat scab, *Gibberella saubinetii* (Mont.) Sacc., and a bacterial disease of wheat, called " black chaff."

WHEAT SCAB CONTROL

In 1928, an experiment which was planned primarily to study the comparative yielding ability of several common wheat varieties was used to study the effect of sulphur in controlling wheat scab. These varieties were sown in 20th-acre plots, separated from each other by 6-foot buffers and alleys. Each variety was replicated seven times in eight plots which were randomized in each experimental block. Four plots were dusted with sulphur on July 17; and thereafter they were dusted at 3 to 4-day intervals until August 29, when the wheat was ripening. At each dusting Kolodust was applied at the rate of 15 pounds per acre. The remaining four plots were left undusted as checks.

In this year a severe epidemic of wheat scab occurred in the experimental plots at Winnipeg. Reward wheat, the most susceptible variety tested, was heavily infected. The effect of sulphur on the amount of rust and scab at harvest time, and on the resulting yield and quality of the Reward wheat, is shown in table 44.

TABLE 44.—Results of dusting with sulphur on the control of wheat scab *(Gibberella saubinetii)*. Effect of dusting Reward wheat on the amount of rust and scab infection, and on the yield and quality of the grain, at Winnipeg, in 1928. (Average results of four 1–200th-acre plots).

Treatment	Per cent leaf rust severity	Per cent stem rust severity	Percentage of plants infected with scab	Yield per acre bushels	Weight per bushel pounds	Increase in yield per acre over check bushels
Dusted....................	22	10	13	27·6	63	8·4
Undusted..................	50	45	80	19·2	61	–

It is apparent from this preliminary test that dusting with sulphur markedly prevented the development of scab. At harvest time disease data were estimated on the percentage basis after actual counts of 1,000 plants chosen at random in the dusted and undusted plots had been made. A study of the experimental data reveals a very decided difference in the percentage of plants infected with scab in favour of the dusted plots, and in the absence of a heavy rust infestation, it would seem that the improvement in yield and quality was due in part, at least, to the control of wheat scab. The results are of interest and emphasize an extremely important point in favour of sulphur dusting for the control of diseases of cereal crops.

Black Chaff Control

In 1930, an experiment was designed to study the effectiveness of sulphur in controlling leaf and stem diseases of wheat. For this purpose a strain of wheat from a cross, H-44-24 x Marquis, obtained from the Cereal Division, Dominion Rust Research Laboratory, was used. This strain is of no particular agronomic value but is of interest because of its resistance to stem rust and susceptibility to leaf rust. Thus, by eliminating the effects of stem rust, it was hoped by sulphur dusting to determine the relation between leaf rust and yield.

The wheat was sown on May 25 in forty-eight 18-foot rows spaced one foot apart, fifteen grams of seed being sown in each row. The rows were arranged in two series each containing 12 dusted and 12 undusted rows, with border and buffer rows of Garnet wheat. In this arrangement, adjacent dusted and undusted rows were considered as pairs. The experimental yield data were subjected to a statistical analysis. A completely random arrangement of pairs would have been more desirable from the standpoint of the analysis of the results, but it was necessary to have dusted components of different pairs together, so the randomized plan was impractical. The experiment was repeated in 1931.

At harvest time, a very light trace of stem rust was found on a few plants of this strain. Although this strain is considered moderately susceptible to leaf rust, the average severity of infection on the undusted plants was not more than 15 per cent; while only a trace of leaf rust was found on any of the dusted plants. It is quite possible that the physiologic forms to which this wheat hybrid is susceptible were not present in the experimental plots at Winnipeg in 1930 and 1931. The data concerning the control of black chaff by sulphur dust are given in table 45. Heads and stems of dusted and undusted H-44-24 x Marquis hybrid plants are shown in figure 21.

TABLE 45.—Effect of dusting wheat with sulphur at the rate of 15 pounds per acre per application, and at 3-day intervals, on the control of black chaff, in rod rows at Winnipeg, Man., in 1930 and 1931.

Year and dusting period	Treatment of rows	Percentage of plants infected with black chaff	Average weight per 1,000 kernels grammes	Weight per bushel pounds	Yield per acre bushels	Grade	Increase in yield per acre over check bushels
1930	Dusted....	4	35·0	60	30·9	1°	5·9
July 11 — Aug. 20..........	.Undusted..	75	31·1	58·5	25·0	2°	–
1931	Dusted....	17	32·2	62	30·2	1°	2·1
July 10 — Aug. 14..........	Undusted..	61	30·6	61	28·1	1°	–

1930 — $t=5{\cdot}37$. 5% point$=2{\cdot}07$.
1931 — $t=1{\cdot}83$. 5% point$=2{\cdot}04$.

From a study of table 45 it is apparent that frequent applications of sulphur dust largely prevented the development of black chaff. In 1930 the percentage of undusted plants infected with black chaff ranged from 65 to 95, with an average of 75 per cent; whereas the range of the dusted wheat plants was from a trace to 8 per cent, with an average of 4 per cent. In the absence of significant amounts of leaf and stem rust it would seem that the statistically significant increased yield of 5·9 bushels per acre resulting from rows dusted with Kolodust was due in a large part to the control of black chaff.

The experiments in 1930 and 1931 indicated that, when favourable conditions for its development occur, the organism causing black chaff spreads from plant to plant in the field. Insects have been suggested as agents of transmission. It would seem, however, that wind and rain are also important means of dissemination. This disease has not been positively identified as the black chaff disease caused by *Bacterium transluscens* var. *undulosum,* Smith, Jones and Reddy, and described by Smith (87), but in general symptoms the two are identical. As most of the commonly grown varieties of spring wheat appear quite resistant to black chaff, it is not probable that varieties or strains as susceptible as the one used in this experiment will ever be grown commercially. More extensive field experiments will be undertaken to determine the relation between black chaff and the yield of susceptible wheat strains.

FIG. 21.—Heads and stems of H-44-24 x Marquis hybrid showing control of black chaff by dusting with sulphur. Left: head and stems undusted, infected with black chaff. Right: head and stem dusted, not infected.

THE RELATION BETWEEN RUST INFECTION AND YIELD

Goulden and Elders (35), Hayes, Aamodt, and Stevenson (41), and Immer and Stevenson (47) have studied the influence of rust on the yield of cereal crops. The method employed was to correlate rust percentage with yield in a heterogeneous group of varieties and strains. This method gave definite results for the material studied but, with another and entirely distinct group of varieties, the value of the correlation obtained might have been somewhat different. This fact was pointed out by Goulden and Elders (35) in a discussion of the inadequacy of a heterogeneous group of varieties as a purely random sample. Furthermore, it led to the planning of experiments in which the different amounts of rust infection on a single standard variety could be correlated with yield.

In 1929 the experimental data from three small plot experiments, which were designed primarily to determine the effect of dusting with sulphur on the control of rust, were analyzed to determine the relation between the amount of stem rust and the yield of wheat. The experiments were of the Latin Square type and the amounts of stem rust on different replicates were varied by different treatments with sulphur. The detailed results of two of these experiments are given in tables 27 and 32. In the final analysis of the experimental data rust percentages and yields of individual plots were correlated. Goulden and Greaney (36) have already published the results of these studies.

An exactly similar study of the experimental data from sulphur dusted plots was completed in 1930. In a 12 x 12 Latin Square experiment (Table 28) the percentage of stem rust varied from zero to 95 per cent. The crop on these experimental plots was heavy and very uniform. In making a correlation surface for stem rust infection and yield, all the plots were used.

The results of this study are given in the form of a regression graph in figure 22. The correlation coefficient for this group of plots was $-0{\cdot}88$. Its significance was tested by the method given by Fisher (26). This involved calculating—

$$\underline{t} = \frac{r}{\sqrt{1-r^2}} \cdot \sqrt{n^1 - 2}$$

where n^1 is the number of values entering into the correlation. For the coefficient $0{\cdot}88$, the value of t is $21{\cdot}8$. Using Fisher's tables, it is evident that the odds are much greater than 100:1.

An important point in this study was the uniform reduction in yield as the rust varied from low to high percentages. That is, a straight line regression of rust on yield was determined. The linearity of regression was tested by the analysis of variance method as developed by Fisher. It was found that the deviations from the regression straight line were not significant, and this indicated that for any given set of environmental conditions an increase of 10 per cent of rust reduced the yield the same amount as an increase from 70 to 80 per cent.

In this experiment, the reduction in yield for each 10 per cent increase of rust was 2·1 bushels. Expressed in per cent of the average yield (30·3 bushels) of the highest yielding series in the experiment, which represents the average yield to be expected in the absence of stem rust, the reduction in yield of 2·1 bushels due to 10 per cent infection represents 6·9 per cent of the possible yield.

In 1930 a study was made also of the relation between the percentage of rust and the yield of oats. The results of a 10 x 10 Latin Square oat dusting experiment (Table 41) are given in the form of a regression graph in figure 23. In the absence of significant amounts of crown rust the correlation coefficient for this group was $-0{\cdot}66$. Its significance was tested by the method described

above. For the coefficient –0·66, the value of *t* is 7·9. Again, the odds of significance are much greater than 100:1, as for these odds a *t* value of only 2·6 is required.

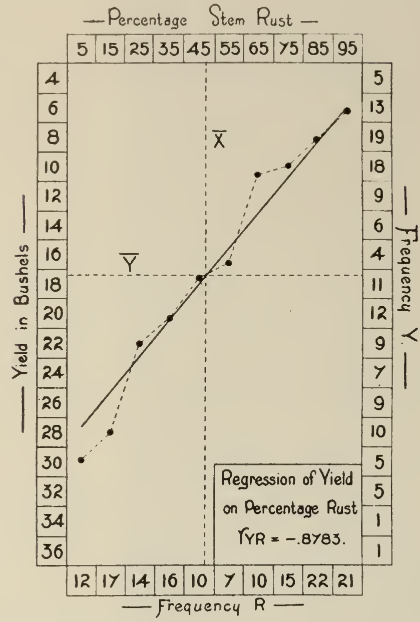

FIG. 22.—Regression of yield on percentage stem rust in plots of Marquis wheat from a 12 x 12 Latin Square experiment in 1930.

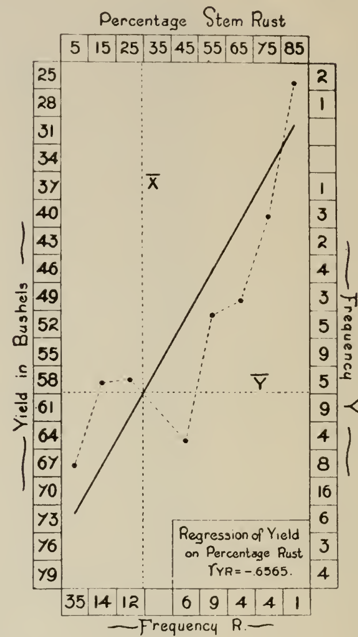

FIG. 23.—Regression of yield on percentage of stem rust in plots of Victory oats from a 10 x 10 Latin Square experiment in 1930.

The determination of the regression of yield on percentage of rust in this experiment, while not entirely satisfactory on account of the low frequency of high percentages, gives, however, an approximate value for the reduction in yield corresponding to a given increase in the percentage of stem rust. The reduction in yield for each 10 per cent of rust is 4·7 bushels. Expressed in per cent of the average yield of the series of plots in which rust was almost completely controlled by sulphur dust, the reduction of 4·7 bushels of oats for an increase of ten per cent of stem rust represents 7 per cent of the possible yield.

In the analysis of the results of another 10 x 10 Latin Square experiment (Table 42), crown rust percentages and yields of individual plots were correlated. A negative correlation coefficient of –0·89 was obtained. In this instance, the odds of significance were very high. From the results of the same experiment the correlation coefficient for stem rust and yield was calculated. For this group a correlation coefficient of –0·88 was obtained for which the value of *t* was 18·6, a very significant value. In 1930, therefore, crown rust and stem rust were found to be significantly associated with the yield of oats.

Field Trials

EXPERIMENTS WITH HORSE-DRAWN AND POWER DUSTERS

From a practical standpoint, the experiments with horse-drawn and self-propelled dusters are the most important phase of the field dusting studies, for such dusters offer the most practical means of applying dusts to large grain fields.

In 1926 and 1927 field trials were made on farms in Manitoba. The results of these preliminary trials have been reported by Bailey and Greaney (3, 4). This phase of the work was continued in 1928, 1929, and 1930. In addition, experiments were undertaken in co-operation with the Dominion Experimental Farms at Morden and Brandon in 1929 and 1930, to devise a wheat dusting schedule for farm practice.

Through the courtesy of the Niagara Sprayer and Chemical Company, Middleport, N.Y., three horse-drawn dusters and a specially designed self-propelled duster, were made available for dusting experiments in Manitoba. The Shunck Manufacturing Company, Bucyrus, Ohio, U.S.A., supplied a "Shunck" duster for the field experiments. Dusting materials were furnished by the Dominion Department of Agriculture, Ottawa, Canada. Electric sulphur, Sulfodust, and Kolodust were the fungicides used.

Methods

Late-sown fields of Marquis wheat growing on summer-fallow were chosen for the farm trials. The development and spread of rust during the early part of each growing season was watched closely, and dusting was commenced when stem rust appeared first in the district, although not necessarily in the experimental fields. Thereafter, the dust treatments were continued at regular intervals until the crop was ripening. The check in each case consisted of part of the same field which was left undusted. Buffer strips of grain between dusted and undusted portions of each field served as protection against dust drift.

The co-operative dusting experiments were arranged so that the same dust treatments were run in duplicate on the Dominion Experimental Farms at Brandon and Morden, and on the College Farm, Winnipeg. In these experiments, Marquis wheat was planted in one-half acre plots. The experiments were of the randomized block type and consisted of four treated plots and an untreated one. The yield data of these experiments were subjected to the analysis of variance test, as previously described.

In all the experiments the yield data were obtained by harvesting from 20 to 40 rod rows selected at random from dusted and undusted portions of each field. These rows were threshed separately and the weighted average was used to calculate the yield in bushels per acre. Whenever possible, the actual field threshing results were also secured. The threshed samples were graded according to Canadian Grain Standards.

Results

Practical farm tests at Winnipeg, Man.—The results of the farm tests carried out during the five years, 1926 to 1930 at Winnipeg, are summarized in table 46. These data show the effect of dusting Marquis wheat with sulphur at the rate of 30 pounds per acre at 7-day intervals from the time rust first appeared until the crop was practically ripe. A photograph of the Niagara self-propelled power-duster, which was used at Winnipeg, is shown in figure 24.

In general, the results for the full five years of the experiments show that 30-pound applications of sulphur, given at 7-day intervals, controlled stem rust of wheat effectively. In 1926 there was too little rust at Winnipeg to permit of definite conclusions, but in 1927, a severe rust year, very satisfactory results were obtained. In that year eight applications of sulphur at the rate of 30 pounds per acre proved to be the most effective, as well as the most practical treatment. A profit per acre of $15.28 was obtained by dusting. Stem rust was light in 1928, and the results of the dusting experiments were not conclusive. In 1929, however, five weekly 30-pound applications, and, in 1930, four dustings

TABLE 46.—Results of field dusting trials with power dusters at Winnipeg, Man., during the five years, 1926-1930. Effect of dusting with sulphur at the rate of 30 pounds per acre, and at weekly intervals, on the amount of rust infection, yield, and quality of Marquis wheat, with the comparative cost of treatment and net gain.

Year and duration of dusting period	Treatment	Size of field (acres)	Total number of dustings	Per cent leaf rust	Per cent stem rust	Weight per bushel	Grade	Yield per acre (bushels)	Increase in yield per acre over check (bushels)	Cost of dust and labour per acre *a* (dollars)	Net gain per acre *b* (dollars)
1926 July 3 — August 13	Dusted	1	5	tr	5	61	2°	44·6	5·2	5·95	1·07
	Undusted	1	0	tr	25	60	2°	39·4	–	–	–
1927 July 18 — September 8	Dusted	1	8	60	35	58	#4	30·2	19·4	10·40	15·28
	Dusted *c*	1	15	50	40	56	#6	29·5	18·7	11·60	13·27
	Undusted	1	0	70	90	44	Feed	10·8	–	–	–
1928 July 10 — July 17	Dusted	6	2	tr	5	61	2°	21·8	–	3·04	–
	Undusted	6	0	tr	5	61	2°	23·1	1·3	–	–
1929 July 12 — August 9	Dusted	30	5	20	5	62	2°	32·5	4·5	4·71	1·72
	Undusted	20	0	30	55	61	2°	22·0	–	–	–
1930 July 15 — August 6	Dusted	20	4	40	25	63	1°	28·0	5·2	4·68	0·65
	Undusted	10	0	45	75	59	2°	22·8	–	–	–

a Depreciation of dusting machine is not included.
b Computed from Winnipeg cash prices for different grades, October 1.
c Dusted at the rate of 15 pounds per acre, and at 3–4 day intervals.

at the same rate, reduced the amount of rust to a marked degree, but the resulting increase in yield and quality was not much more than would cover the cost of the treatment. In 1930, particularly, the low price of wheat was to a great extent, responsible for this result.

Fig. 24.—Niagara tractor power duster with boom dust distributor Width of boom 25 feet.

Fig. 25.—Shunck horse-drawn power duster in operation. The dust is discharged through a wide delivery tube at the side.

Practical farm tests at Graysville, Man.—The results of the Graysville field dusting trials are given in table 47. An illustration of the Shunck duster which was used in some of these trials is shown in figure 25.

In 1927 six 30-pound applications of Kolodust reduced the amount of stem rust from 85 to 35 per cent at Graysville, thereby increasing the yield 12·3 bushels per acre, and improving the grade of Marquis wheat from No. 5 to No. 3 Northern. This represented a net profit of $11.87 per acre due to the control of stem rust alone. Leaf rust was not satisfactorily prevented in 1927 by weekly dust treatments. These results are from practical farm tests and the cost data cover the cost of sulphur and the labour involved in its application. The 1927 results would have been even better had the crop ripened more quickly, or if another dust application had been made. Unfortunately, the supply of sulphur was exhausted on August 13 and the crop was not harvested until September 7.

TABLE 47.—Results of field dusting trials with power dusters at Graysville, Man., during the 4 years, 1927-1930. Effect of sulphur dust applied at the rate of 30 lbs. per acre, and at 7-day intervals, on the amount of rust infection, yield, and quality of Marquis wheat, with the comparative cost of treatment and net gain.

Year and duration of dusting period	Treatment	Size of field acres	Total number of dustings	Per cent leaf rust	Per cent stem rust	Weight per bushel pounds	Grade	Yield per acre bushels	Increase in yield per acre over check bushels	Cost of dust and labour per acre *a* dollars	Net gain per acre *b* dollars
1927	Dusted *c*	8	6	60	35	60	3°	22·6	12·3	6·00	11·87
July 21 — August 13	Undusted	1	0	65	85	53	#5	10·3	–	–	–
1928	Dusted	10	3	tr	15	63	2°	25·6	4·6	2·38	3·04
July 9 — August 27	Undusted	5	0	tr	35	61	2°	21·0	–	–	–
1929	Dusted	5	4	20	25	62	2°	15·7	3·5	4·04	1·34
July 12 — August 3	Undusted	1	0	25	75	60	3°	12·2	–	–	–
1930	Dusted	30	4	30	35	62	1°	27·7	13·4	4·68	5·93
July 15 — August 6	Undusted	30	0	35	75	59	2°	14·3	–	–	–

a Depreciation of dusting machine is not included.
b Computed each year from Winnipeg cash prices, October 1.
c Dust applied at the rate of 25 pounds per acre, and at 3-4 day intervals.

In 1928 four 30-pound dustings gave satisfactory stem rust control. The retarded development of rust together with the early ripening of the grain prevented, in general, any serious loss to the crop, except in some late-sown fields. The results show that even in a year when damage from rust is not very appreciable, dusting with sulphur does enhance the value of the crop sufficiently to return a profit after all deductions for materials and labour have been made. Similar results, demonstrating that large fields of wheat can be successfully treated with sulphur by means of horse-drawn and self-propelled dusters, were obtained in 1929.

Four 30-pound applications of sulphur at Graysville in 1930, by controlling rust, increased the yield 13.4 bushels per acre and raised the quality of the grain from 2 Northern to 1 Northern, thereby giving an increased value of $5.93 per acre. The low price of wheat that year substantially reduced the net profit from the dusting operation.

Co-operative dusting experiments.—The results of dusting Marquis wheat with sulphur at Morden, Brandon, and Winnipeg in 1929, are given in table 48. The type of horse-drawn duster used in these field tests is illustrated in figure 26.

Fig. 26.—Niagara horse-drawn power duster with boom dust distributor. Width of boom 30 feet.

In 1929 rust was very light at Morden, moderately heavy at Winnipeg, and heavy at Brandon. Dust applied at the rate of 20 pounds per acre, and at 3 to 4-day intervals, gave the most effective control. On the other hand, however, weekly 40-pound dustings were almost as effective as 20-pound applications and may be considered a more practical treatment. From a study of table 48 it is evident that the effect of dusting was not very noticeable at Morden, while at Brandon and Winnipeg the results were much more conclusive. Examined in the light of the standard error, mean differences in yield between the respective dust treatments and checks were statistically significant, with the exception of the weekly 20-pound treatments. However, yield differences between individual dust treatments were not significant.

TABLE 48.—Results of dusting one-half acre plots of Marquis wheat with sulphur by means of horse-drawn power dusters at Morden, Brandon and Winnipeg, in 1929. (Dusting period: July 12 to Aug. 14).

SUMMARY OF RESULTS

Station	Amount of dust per acre pounds	Interval between dustings days	Per cent stem rust severity	Yield per acre bushels	Weight per bushel pounds	Grade	Increase in yield per acre over check bushels
Morden	20	3 to 4	tr	11·0	63	2°	1·0
	20	7	10	10·5	62	2°	0·5
	40	7	tr	10·7	62	2°	0·7
	40	7	5	11·0	63	2°	1·0
	0	Check	15	10·0	62	2°	–
Brandon	20	3 to 4	5	40·0	64	1°	6·6
	20	7	30	36·0	63	1°	2·6
	40	7	15	41·0	63	1°	7·6
	40	7	10	38·0	63	1°	4·6
	0	Check	70	33·4	62	2°	–
Winnipeg	20	3 to 4	5	34·7	63	1°	7·5
	20	7	20	30·4	63	1°	3·2
	40	7	18	33·0	63	1°	5·8
	40	7	10	32·8	63	1°	5·6
	0	Check	56	27·2	60	2°	–

Standard error of one treatment=1·39.
Minimum significant yield difference=4·2 bushels per acre.

YIELD ANALYSIS OF VARIANCE

Source of variance	Sums of squares	Degrees of freedom	Variance of mean square	$\frac{1}{2}\log_e$
Districts	3,293·65	2	1,646·82	–
Replicates	120·68	2	60·34	–
Treatments	72·52	4	18·13	1·4488
Districts and treatments	34·14	8	4·27	–
Error	31·15	8	3·89	0·6793
Total	3,552·14	24	....	$Z=0\cdot7695$

5% point=0·6725

In 1930 a similar experiment was undertaken, the data concerning which are given in table 49. In general, the 1930 results confirm the findings of 1929. Rust developed vigorously on the very late crop at Winnipeg in 1930. Even heavy frequent dust applications failed to prevent its spread, and the yield results were not important. The results at Brandon and Morden show that five 60-pound sulphur applications given at 10-day intervals were not so effective as six 40-pound weekly dustings. Semi-weekly 20-pound applications gave the best control of rust in 1930, while weekly applications at the same rate were least effective. An analysis of the yield figures showed that, at Morden, the differences between respective dust treatments and the undusted checks were significant, but the individual differences between dust treatments were exceeded by the limit set for significance.

TABLE 49.—Results of dusting plots of Marquis wheat with Kolodust by means of horse-drawn power dusters at Morden, Brandon, and Winnipeg, in 1930. (Dusting period: July 11 to August 16).

SUMMARY OF RESULTS

Station	Amount of dust per acre pounds	Interval between dustings days	Per cent leaf rust severity	Per cent stem rust severity	Yield per acre bushels	Weight per bushel pounds	Grade	Increase in yield per acre over check bushels
Morden	60	10	35	45	22·6	51	#4	12·6
	40	7	25	35	25·7	55	3°	15·5
	20	7	45	60	21·4	52	#4	11·2
	20	3 to 4	15	25	28·3	55	2°	18·1
	0	Check	55	85	10·2	44	Feed	–
Brandon	60	10	35	30	31·2	59	2°	1·5
	40	7	20	15	33·9	60	1°	4·3
	20	7	30	25	34·9	61	1°	5·2
	20	3 to 4	15	10	39·2	62	2°	9·5
	0	Check	60	85	29·7	52	#5	–
Winnipeg	60	10	50	65	7·4	52	#5	4·2
	40	7	40	60	7·6	49	#6	4·4
	20	7	45	80	4·7	44	Feed	1·5
	20	3 to 4	30	40	7·8	53	#5	4·6
	0	Check	55	95	3·2	41	Feed	–

Standard error of one treatment = 2·41.
Minimum significant yield difference = 7·23 bushels per acre.

YIELD ANALYSIS OF VARIANCE

Source of variance	Sums of squares	Degrees of freedom	Variance of mean square	$\frac{1}{2}\log_e$
Districts	4,237·14	2	2,118·57	–
Replicates	19·20	1	19·20	–
Districts and replicates	19·36	2	9·65	–
Treatments and districts	157·36	8	19·67	–
Treatments and replicates	174·17	4	43·54	–
Treatments	393·16	4	98·29	2·2939
Error	92·85	8	11·61	1·2259
Total	5,093·24	29		$Z = 1·0680$

5% point = 0·6724

General Considerations

The results obtained in the five years, 1926 to 1930, demonstrate the practical possibilities of sulphur dusting for rust control. A technique of dusting large fields of wheat by means of horse-drawn and tractor dusters has been developed. The results emphasize the importance of starting to dust when rust first appears, and then thoroughly protecting the growing plants until they are practically ripe. It is realized, however, that more efficient dusting machines must be devised. The mechanical difficulties involved in the development of a machine that will effectively dust a large field of grain with the least amount

of injury to the standing crop are not wholly unsurmountable. Indeed, considerable progress has already been made towards the development of a satisfactory cereal crop duster.

Economic factors will play an important part in determining the value of dusting for rust control. If dusting is to be a practical method of controlling rust, it must, of course, produce a net profit to the grower over a period of years. In this respect it is similar to any other dusting or spraying problem. From the results presented in tables 46 to 49 it is apparent that in years when severe rust epidemics occur dusting will control rust satisfactorily. However, as the probability of rust epidemics cannot be predicted with any degree of certainty, it would be advisable for the grower to dust every year.

Much has been learned regarding the technique of dusting large fields of grain. The results of the five years' experiments on private and experimental farms located in various parts of Manitoba indicated that rust can be controlled practically and effectively in large fields. Furthermore, the increase in yield and quality resulting from dusting was more than enough to cover the cost of depreciation of duster, materials, and labour. Sufficient evidence has been provided to show that under ordinary conditions weekly applications of sulphur at the rate of 30 pounds per acre, made from the time rust first appears until the crop is ripening, a period of from 4 to 6 weeks, constitute an effective dusting schedule for Manitoba.

AEROPLANE DUSTING EXPERIMENTS

The first use of aeroplanes for combatting plant diseases was made in Ohio, U.S.A., in 1921. In that year they were employed in applying insecticides to forest trees. The success achieved in this experiment suggested the use of the aeroplane to combat the cotton boll weevil (*Anthonomus grandis* Boh.). Coad (17) states that this method of spreading calcium arsenate is entirely practical for the control of this destructive insect pest, and that during 1925 over 50,000 acres of cotton were dusted commercially.

Employment of aeroplanes for forest pest control is now an accomplished fact in Germany, Canada, and other countries. The subject has been reviewed by Wolff and Krause (103), Krieg (52), and Swaine (93).. Korotkikh (51) has given a brief account of aeroplane dusting experiments made in 1925 by the Russian Government against the European migratory locust, *Locusta migratoria.* Aeroplane dusting for cotton boll weevil control has been discussed by Post (78), Coad, Johnson, and McNeill (18), and Hinds (43). Imms (46) summarized briefly the results of aeroplane dusting in combating injurious insects. It is noteworthy that in recent years large acreages of forest trees, pecan, tobacco, sugar cane, peaches, cranberries, apples, and citrus fruits, as well as large Catalpa, rubber, and cotton plantations have been dusted from the air. The use of aeroplanes for the application of dust fungicides and insecticides constitutes an advanced step in plant disease control.

The success which has attended the use of the aeroplane in the application of dry insecticides for the control of the cotton boll weevil and other destructive plant pests, suggested the possibility of this method for applying dry fungicides for the control of rust. In 1927, 1928, and 1930, a series of co-operative aeroplane dusting experiments between the Canadian Department of Militia and Defence, Civil Air Operations Branch, and the Canadian Department of Agriculture, were carried on in Manitoba for the purpose of determining the value of aeroplane dusting for the control of stem rust.

Methods

The fields selected for these tests consisted of large continuous areas of Marquis wheat growing on summer-fallow, and conveniently located to satisfactory landing bases. In 1927 areas of approximately 250 acres each were chosen in the Morden, Graysville, and Portage Plains districts of Manitoba. In 1928 two fields representing an area of 250 acres was used in the Morden district, and one field of 140 acres was selected at Morris. In 1930 eight fields of Marquis wheat on summer-fallow, comprising 714 acres located on the Portage Plains, were used for the experiments.

The Canada Civil Air Operations Branch provided the dusting plane and equipment, also the pilot and mechanics, while the ground staff, equipment, and dust materials were provided by the Canada Department of Agriculture. The machine, a Keystone Puffer (Fig. 27), detailed for the dusting operation, was of special construction and of the type recommended for the dusting of cotton fields. Kolodust and Electric sulphur were the fungicides used in all the aeroplane tests.

Fig. 27.—Dusting plane (Keystone Puffer) used for aeroplane dusting experiments in Manitoba. Loading the machine with sulphur dust. Hopper capacity 600 pounds.

Flying operations were in charge of an officer of the Royal Canadian Air Force, Winnipeg Air Station. The pilot's skill in handling and manipulating the machine under very difficult air conditions contributed greatly to the success of the experiments. The writer acknowledges his indebtedness to Flight Lt. T. M. Shields and Pilot Officer P. Cox for their enthusiastic co-operation in carrying out the experiments, and for their excellent services, and to Squadron Leader N. R. Anderson, Officer Commanding, Winnipeg Air Station, for his interest, generosity, and courtesy.

Preliminary dusting trials were arranged to determine the rate and spread of sulphur dust. By regulating the hopper valve aperture and the speed of the machine, very close approximations to any desired rate of dust application could be obtained. A description of the hopper and dust distributor is given with

figure 28. During dusting operations the machine was flown at a height of from 10 to 15 feet from the ground and at a speed of 100 miles per hour. Under favourable air conditions, and with the hopper valve opened to $1\frac{3}{4}$ inches, the machine would dust a strip of crop from 90 to 100 feet wide. Under these conditions the fungicide was applied uniformly at the rate of 25 pounds per acre.

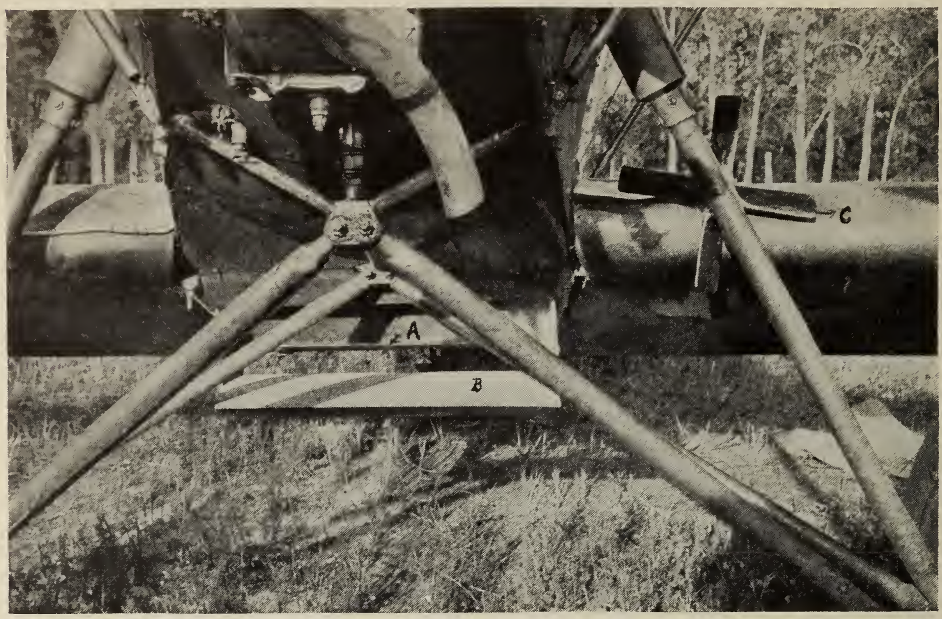

Fig. 28.—Keystone Puffer showing the detailed construction of (A) hopper-valve, (B) dust distributor, and (C) small propeller geared to the agitator inside of hopper. The hopper-valve shown at A is a sliding door which is opened by the pilot from the cockpit. The dust falls on the distributor (B), and is caught in the "slip stream", and is immediately converted into a dense cloud of dust which floats out with a spiral motion behind the plane.

The experimental fields were plainly marked out with large red flags. The general manner of dusting a field consisted in flying back and forth over the growing crop, permitting the dust clouds to overlap very slightly. With straight-away dusting flights, at least one-half mile long, and with landing bases conveniently situated, it was quite possible to dust 100 acres of wheat per hour. Photographs of the dusting plane in operation are shown in figures 29 and 30.

Dusting operations were carried on in the early morning or late evening when usually the plants were damp with dew and there was the least air movement. During dusting operations men stationed at each end of the field would, by means of flag signals, indicate to the pilot the path which he was to traverse. After the machine had passed, the men would move a sufficient distance across the field to allow for the spread of the dust and take up new positions to direct the pilot in placing the next dust-swath. Thus, reasonable accuracy and uniformity in the rate of dust application was obtained.

A part of each experimental field was left untreated as a check. The check was separated from the dusted part of the field by a buffer strip at least 250 feet in width, which served as protection to the check against dust drift. It was much easier to maintain satisfactory check plots when the fields were large and continuous.

The development of rust was watched closely during the dusting period. Dusting operations were commenced when a trace of rust first appeared in the district, but not necessarily in the fields selected for dusting. Rust notes were taken a few days after the field had received the final application of dust. The percentage of leaf and stem rust infection of each dusted and undusted area were recorded according to the usual standard.

FIG. 29.—Photograph of dusting plane immediately after the hopper-valve was opened. Notice that the dust is forced downward, and due to the rotational flow of air from the propeller it spreads in a spiral arrangement. With favourable air conditions the machine was capable of thoroughly dusting a strip of wheat 100 feet in width.

Yield data were obtained by harvesting rod rows chosen at random from each treated and untreated area. The number of rows -harvested for yield determinations depended upon the size of the field and the uniformity of plant growth. Usually, not less than forty rod rows were harvested from each section of an experimental field. The average of these samples was used to calculate the yield in bushels per acre. Threshed samples of the grain were submitted to officials of the Western Grain Inspection Division, Winnipeg, Manitoba, for quality and grade determinations.

Results

Bailey and Greaney (4) have published detailed summaries of the results of the 1927 aeroplane dusting tests. A brief summary of the results obtained from representative fields in each of the aeroplane dusting areas in 1927, 1928, and 1930, is presented here. The experimental data are given in table 50.

In 1927 severe epidemics of leaf and stem rust of wheat occurred in Manitoba. Conditions in that year were exceedingly conducive to the development

of rust and militated against the effectiveness of aeroplane dusting. The results, however, were very encouraging, and emphasized the importance in aeroplane dusting of four factors, namely: time of dust application, uniformity of application, rate of application, and weather conditions following dust application. As shown in table 50, the Graysville results were very satisfactory. Four 15-pound applications of sulphur effectively prevented rust and markedly increased the yield. From the 1927 results, however, it was concluded that heavier rates of application than those used in 1927 are desirable for aeroplane dusting.

FIG. 30.—Dusting plane in operation showing behaviour of dust after being discharged from hopper. The machine is flying at an altitude of from 10 to 15 feet.

Owing to relatively little rust development, the tests in 1928 were of no great value in determining the question of what rates and frequencies of sulphur dust application, when made by aeroplane, will effect the most satisfactory and practical control of rust. As is shown in table 50, it will require more significant evidence to determine the limits of effectiveness of dust treatments, as well as the practicability of aeroplane dusting. The increase of 5·8 bushels in the Morden field is interesting. Field observations indicated that the difference obtained between treated and untreated portions of this field could be accounted for by the general effectiveness of sulphur in controlling leaf and stem diseases of wheat other than rust.

TABLE 50.—Results of dusting Marquis wheat with sulphur by aeroplane for the control of leaf rust and stem rust. Effect of sulphur on the amount of rust infection, and on consequent yield, and quality of grain in Manitoba, in 1927, 1928, and 1930.

Year	Field	Treatment	Size of field	Rate of sulphur per acre	Date dusted		Per cent leaf rust at harvest	Per cent stem rust at harvest	Weight per bushel	Grade	Yield per acre	Increase in yield per acre over check
			acres	pounds	July	August			pounds		bushels	bushels
1927	Morden	Dusted	70	12	13, 20, 28	6	35	75	58	#4	18·8	0·7
		Undusted	11	0	—	–	35	85	56	#4	18·1	–
	Portage	Dusted	45	15	18	2	40	75	58	3°	21·1	0·3
		Undusted	40	0		–	45	80	58	3°	20·8	–
	Graysville	Dusted	75	16	14, 21, 28	4	40	45	61	2°	33·8	13·0
		Dusted	30	15	14, 21, 28	4	40	35	63	1°	40·7	19·9
		Undusted	20	0	–	–	55	75	59	#5	30·8	–
1928	Morden	Dusted	110	25	17, 24, 31	8	tr	10	62	3°	25·1	5·8
		Dusted	45	25	24	–	tr	15	62	3°	19·0	–
		Undusted	40	0	—	–	tr	15	62	3°	19·3	–
	Morris	Dusted	115	30	18, 25	1	tr	5	62	2°	30·1	0·6
		Undusted	25	0	—	–	tr	5	62	2°	29·5	–
1930	Ferris	Dusted	60	20	18, 25, 31	–	20	36	61	1°	30·8	3·7
		Dusted	60	20	18, 21, 25, 29	1	10	10	63	1°	37·2	10·1
		Undusted	40	0	—	–	25	55	59	1°	27·1	–
	Ferguson	Dusted	51	30	19, 25, 31	6	30	35	59	1°	28·6	6·2
		Undusted	50	0	—	–	40	70	59	1°	22·4	–

In 1930 eight fields, comprising 714 acres, located on the Portage Plains, Man., were used for the aeroplane experiments. Five hundred and twenty-eight acres were dusted; while two hundred and eighty-six acres were left untreated as check areas. An extended period of dry weather in July checked the development of both leaf and stem rusts and ripened the grain uniformly and rapidly. Although stem rust was moderately heavy, and leaf rust was generally present in all wheat fields on the Portage Plains in 1930, in only a few cases were yields significantly reduced by these diseases, the quality of the grain being not noticeably affected. Practically every field of Marquis wheat in the Portage district this year graded Manitoba No. 1 Northern. The conditions under which the 1930 experiments were made were not very satisfactory, and the results do not permit of definite conclusions.

As shown in table 50, the amounts of stem rust in the fields used in 1930 for the aeroplane experiments were markedly reduced by dusting. Owing to the fact that it is difficult to dust quickly and thoroughly the entire leaf surface of millions of plants in a field of wheat, infrequent aeroplane sulphur applications were of no great value in preventing leaf rust. Five 20-pound applications of sulphur dust reduced the amount of stem rust infection in one field from 55 to 10 per cent, and increased the yield 10·1 bushels per acre, although the quality of the grain was not improved by dusting. It should be pointed out that, owing to the low price of wheat this year, even this gain in yield would not cover the cost of aeroplane dusting.

General Considerations

In summarizing the aeroplane dusting work it may be said that dusting by aeroplane is a practical and effective means of applying sulphur to large areas of cereal crops. Large fields of grain can be rapidly and thoroughly dusted by this method. Since there is more flying involved in manouvering at the ends of the fields than in the actual dusting operations, the method is suited to large fields. In some districts of the spring-wheat region of Western Canada, repeated rust losses have forced a considerable degree of diversification in agriculture, and the wheat acreage has been broken up into blocks of from 30 to 60 acres. Undoubtedly, this condition would limit the usefulness of aeroplane dusting in these districts.

The technique of aeroplane dusting for the control of cereal rusts has been developed. This method has been satisfactorily employed in checking the development of rusts and preventing their spread over large areas. If aeroplane dusting is to be a practical method of rust control, it will, of course, depend on the average net profits to the farmer. In the last analysis, economic factors will determine whether or not aeroplane dusting can be made a profitable farm practice. Regardless of the immediate results which have been obtained, the efforts spent in the experiments have been well repaid in the practical development of aeroplane dusting for general use against destructive outbreaks of certain plant diseases.

V. DISCUSSION AND CONCLUSIONS

The experiments have established that both copper and sulphur dusts are toxic to germinating aeciospores and urediniospores of cereal rust fungi. Laboratory studies on the fungicidal activity of sulphur support the findings recently reported by McCallan and Wilcoxon (69) that some product of sulphur is the toxic principle and that the production of the toxic product is dependent upon association with the living spore. In the present studies no evidence has been found to support the viewpoint that the element itself is the active agent.

In the greenhouse experiments rust infection was completely prevented when the plants were dusted with sulphur before they were inoculated with aeciospores and urediniospores. When sulphur dust was applied after inoculation, the inhibiting effect was not so satisfactory, especially when the conditions prevailing between inoculation and dust application were favourable for infection. Sulphur applied three hours after inoculation was quite ineffective in reducing infection.

The experiments indicate that when once the germ tubes penetrate a host plant, their further development is beyond the influence of an external fungicide, and that subsequent applications of sulphur are of value only in that they prevent further infection. In dusting practice, therefore, the ideal conditions would be to have the plants protected with sulphur before infection takes place, and then to dust the plants often enough to keep them protected while they are in a susceptible stage of development.

In a search for effective and economical dust fungicides it was found that, of those tested, finely-divided sulphur dusts were the best for rust control. In practice, particle size must be considered in the evaluation of sulphur dusts as fungicides. It would seem that any pure sulphur dust of 300-mesh fineness would give very satisfactory results. Oxidized sulphur dusts were not so effective against rust as ordinary dusting sulphurs, while copper dusts were quite ineffective for the control of cereal rusts.

In all the field experiments entirely satisfactory results were obtained by applying the initial application of sulphur dust to the growing plants when stem rust was first found in the district. It is realized, however, that this method is only possible when the primary field infections are watched closely by experienced workers. A more practical method would be to begin dusting on some particular date or when the crop has reached a particular stage of development. Observations over a long period of years indicate that, in Manitoba, stem rust does not appear until the wheat plants are in the late "boot" or early "heading" stage. Satisfactory results were obtained by applying the first dust at this time. Unfortunately, however, seasonal and regional differences make it impossible to give a definite date or stage of plant growth at which rust first appears which would be applicable in all seasons and in all regions. In cereal rust control, the time at which initial dustings are made is an extremely important factor in the resultant effectiveness of the treatment. Early dust applications prevent the accumulation of viable inoculum on the plants, and thus makes the subsequent control of rust relatively easier. In Manitoba and Saskatchewan dusting should be commenced when first rust is noticed in wheat and oats. Usually, wheat dusting need not be started until the plants are in head.

In dusting practice, distribution, coverage, and adhesiveness of sulphur dusts were greatly influenced by such meteorological factors as rain, dew, and wind. Although finely-divided sulphur dusts were exceedingly good protectants for long periods during relatively dry conditions, they did not adhere well to the leaves and stems of cereal plants during wet weather. The effective period of a single application of sulphur was much shortened in rainy weather. It is therefore advisable to dust immediately after heavy rains, for then the plants are protected until another rain comes, and hence the number of dust applications can be considerably reduced. Besides, the dust adheres better to wet plants. Wind, at the time dust is being applied, seriously interferes with the dusting operation itself and with the effectiveness of the treatment. As the air is usually stiller in the early morning and late evening than at any other periods of the day, these times were found most advantageous for dusting, particularly the morning, when dew caused the dust to adhere better to the plants.

One point made very evident by the experiments was the importance of thoroughly protecting the whole surface of the plant with a covering of sulphur.

It was a relatively easy matter to dust small plots properly with a hand duster, but to dust every plant in a large field of grain quickly and thoroughly with a machine was a much more difficult problem. The results of five years' experiments with horse-drawn and self-propelled dusters demonstrated that large fields of grain could be thoroughly dusted by these means. Moreover, during the course of this investigation the cost of the treatments was not prohibitive. As a matter of fact, in years when rust was severe, a substantial profit was made.

The technique of applying sulphur dust by means of an aeroplane for rust control has been developed. After three years' work it can be said that aeroplane dusting is a practical and effective means of dusting large areas. At the present time, owing to the low price of grain, this method cannot be applied profitably in Western Canada.

In Manitoba where the dusting period is from 4 to 6 weeks, there is some evidence that rust may be satisfactorily prevented by one or two well-timed heavy dust applications. There is definite evidence to show that in light rust years, applications of 15 to 20 pounds per acre, made at 7-day intervals, will control rust. In severe rust years, however, 30-pound applications at intervals of 4 days will insure effective and economical control of stem rust of both wheat and oats, and reduce by a very significant degree the amount of leaf rust and crown rust. Relatively light sulphur dust applications at fairly close intervals will give the most satisfactory results in preventing such diseases as wheat scab, black chaff of wheat, and some of the minor leaf and stem spotting diseases of cereal crops. It is hardly necessary to point out that, to a very large extent, the rate and frequency of dust application will have to be decided each year, and that they may have to be adjusted as the summer advances, according to the weather conditions, the progress of the rust, the stage of plant development, as well as according to the means at one's disposal of applying the dust, and the control already achieved by previous applications.

The data presented in this paper are of interest in that they permit of a very accurate estimation of the amount of damage actually caused by rust under field conditions. It is evident from the results that enormous losses in yield are suffered annually. From the results of studies on the relation between the amount of rust and the yield of grain, it is apparent that in estimating rust damage cognizance must be taken of low as well as of high percentages of rust. In 1929 it was found that the first 10 per cent of stem rust reduced the possible yield of wheat about 7 per cent, and that for each additional 10 per cent of rust the yield was reduced by a like amount. In 1930 a similar reduction was found in the yield of oats. In all the experiments the regression of yield on percentage stem rust was linear, indicating that an increase in rust, for example, from 10 to 20 per cent, will reduce the yield the same amount as an increase of rust from 60 to 70 per cent.

It is obvious that the real value of dusting lies in the prevention of the enormous losses caused by cereal rusts. The prevention of leaf rust and stem rust of wheat by dusting at Winnipeg in 1925 resulted in an increase in yield of Marquis wheat of 37·4 bushels per acre, or about 200 per cent. In 1927, dusting increased the yield 24 bushels per acre, or 175 per cent; and in 1930, 24 bushels per acre, about 400 per cent. By the control of crown rust and stem rust in 1930, the yield of oats was increased 45 bushels per acre, or about 153 per cent. Furthermore, the quality of the grain was greatly improved. From these data it is quite evident that losses due to rust could be very effectively reduced by the use of fungicidal dusts.

In general, it may be stated that the results of six years of field experimentation demonstrated clearly the effectiveness of sulphur dusting for the control of rust. Leaf and stem rusts of both wheat and oats were satisfactorily controlled in small plots and large fields, even in the presence of severe natural epidemics.

Effective, practical, and, in many cases, profitable dusting schedules were developed for the prevention of these diseases. Furthermore, it was found that frequent applications of sulphur dust prevented the development of scab, black chaff, and some of the minor leaf and stem spotting diseases of wheat to a marked degree. The sulphur dusting method should be of immediate and distinct value to experimentalists, seed growers, and grain exhibitors in the spring-wheat area of Canada and the United States. Whether or not sulphur dusting for the control of cereal rusts can be made a profitable agricultural practise will depend largely on such economic factors, as, the cost of production, relative grain prices, cost of dust fungicides and dusting equipment. More intensive cultural practices would cause a higher yield per acre, and hence would enhance the possibilities for the control of rust by dusting with sulphur. On the other hand, the general introduction of commercially desirable rust-resistant carriers would remove the necessity of providing protection from rust.

VI. SUMMARY

1. An investigation to determine the possibility of preventing the enormous losses due to cereal rusts by the use of fungicidal dusts was carried on during the six years, 1925-1930, at the Dominion Rust Research Laboratory, Winnipeg, Manitoba. The experimental phases of the investigation consisted of laboratory, greenhouse, and field studies.

2. The comparative toxicity of copper and sulphur dusts to germinating aeciospores and urediniospores of cereal rusts was determined. It was found that sulphur dusts and copper dusts both exhibit a high degree of toxicity. Germinating rust spores were very sensitive to sulphur and sulphur compounds.

3. The toxicity of sulphur to rust spores is apparently not due to the element itself but to one of its products. It is believed that the production of the toxic principle is dependent upon intimate association with the living spore.

4. The fungicidal effectiveness of sulphur and copper dusts was tested on growing plants in the greenhouse and it was found that sulphur dusts were much more effective against rust pathogens than were copper dusts. Sufficient copper dust to check rust caused injury to the plant.

5. Sulphur dust acts as a protectant. Rust infection was completely prevented when sulphur was applied before inoculation. Its effectiveness was reduced in proportion to the time elapsing between dust application and inoculation. Once the fungi penetrate the host plant subsequent applications of sulphur are of value only in that they prevent further infection.

6. The fungicidal efficiency of sulphur dusts was studied under different conditions of humidity and temperature in the greenhouse. The presence of abundant moisture at the time of and subsequent to inoculation with rust spores, greatly reduced the value of sulphur dust. In these experiments, the action of sulphur was not influenced by temperature.

7. Each year during the six-year period, 1925-1930, a comprehensive series of small plot studies were planned and carried on at Winnipeg. In addition, large field experiments both with ground dusters and with an aeroplane duster were conducted for several years on private and experimental farms in Manitoba.

8. Each year during the period of the investigation, applications of a suitable sulphur dust, well-timed and properly applied, prevented rust and other leaf and stem diseases of cereal crops to a marked degree. Practical and effective dusting schedules were developed for controlling stem rust of wheat and oats in small plots and large fields. Aeroplane dusting was found practical and effective in preventing rust, but the cost involved rendered this method of applying sulphur dust unprofitable under present circumstances.

9. Of the many brands of dust used, finely-divided sulphur dusts were the best for rust control. The fungicidal effectiveness of sulphur was increased in proportion to the fineness of its particles. Ordinary pure sulphur of 300-mesh fineness gave very satisfactory results.

10. The most opportune time at which to commence dusting is when rust first appears on the plants. In Manitoba, stem rust does not appear until Marquis wheat plants are in the late " boot " or " early heading " stage. The most satisfactory results were obtained by making initial sulphur applications at this time. Subsequent applications were made at regular intervals while the plants were in a susceptible stage of growth. Usually the length of the sulphur-dusting period was from 4 to 6 weeks. In Manitoba the most advantageous times for dusting were the early morning and late evening, and immediately after rains.

11. The effect of sulphur on the amount of rust infection and yield was least with light infrequent dust applications, and greatest with heavy frequent ones. For the control of stem rust of both wheat and oats the most economic rate of application was 30 pounds per acre at each application. In severe rust years, the most satisfactory interval between dustings was 4 days. In light rust years, applications of 15 pounds per acre made at 7-day intervals controlled rust. Relatively light sulphur applications made at close intervals gave the most satisfactory results in preventing leaf rust of wheat and crown rust of oats, and some of the minor leaf and stem diseases of wheat. There appeared to be no fertilizer effect from sulphur applied, even in large amounts, to the soil.

12. The actual damage caused by cereal rusts under natural field conditions was computed. The data presented in the form of correlation coefficients and regression equations show that uniform increases in rust result in uniform reduction in yield. At Winnipeg, in 1930, each 10 per cent of stem rust reduced the yield of wheat 8·2 per cent. Based on this result the total percentage-loss in yield in that year was 73 per cent. The loss in yield due to stem rust of oats in 1930 was 49 per cent.

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